# QUANTIFICATION OF THE COMPACTION PROBLEM OF SELECTED VINEYARD SOILS AND A CRITICAL ASSESSMENT OF METHODS TO PREDICT SOIL BULK DENSITY FROM SOIL TEXTURE

By

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# DECLARATION

I the undersigned, hereby declare that the work contained in this dissertation is my own work and has not previously in its entirety, or in part, been submitted to any University for a degree.

L. VAN HUYSSTEEN

Date : 1989 - 03-03

"If we lack concept, we run the risk of monumentally achieving what was not worth doing in the first place."... "It is a mistake to believe that research is done in the laboratory. It is done in the head - the laboratory merely confirms or rejects what the mind conceives" (Sidney Harris).

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# ABSTRACT

Besides this overall abstract, each chapter has a separate abstract under its own heading.

Soil compaction is a problem common to many South African vineyard soils, and it has substantial adverse effects on root growth. Although literature reveals that much is known about the inherent soil properties affecting compactibility, extrapolation beyond the sample population remains a problem. The permanence of expensive soil loosening actions is uncertain on some soils, because a measure of the bulk density to which the soil will recompact is not available. This study was conducted to document the compaction problem in vineyard soils in a total perspective. The final objective was to predict both maximum compactibility (MBD) and equilibrium field bulk density (FBD) from soil textural data, and to use other physical soil properties, *e.g.* soil structure, modulus of rupture, and air-to-water permeability ratio as background information to explain observed and predicted soil bulk densities (BD).

As a starting point, the effect of artificial subsoil compaction on grapevine shoot and root growth was studied in 85 $dm^3$ pots. In a follow-up experiment, three deep tillage methods were evaluated in terms of the size and looseness of the rooting volume. The soil in this experiment had a natural dense subsoil. Subsequently, 71 soil samples comprising of a wide textural range, and representing different degrees of compaction in the field, were collected from the most important viticultural areas of the Republic of South Africa. Soils were tested for various soil physical and chemical properties. Regression techniques were used to relate soil compactibility to soil texture or some measure of soil structure. Finally, a packing model of Gupta and Larson was tested for its applicability to predict soil BD.

No critical BD or penetrometer soil strength (PSS) for the impedance of grapevine roots was found in the pot experiment for any of the five different soils investigated. However, aboveground grapevine performance decreased linearly with increasing subsoil BD's. Very low optimum compaction levels have been suggested, but this needs further investigation in field trials. In the field experiment, potential rooting volume was defined by BD and PSS values. Great care should be taken to define the position of PSS and BD measurements. During sample collection, the many types of compaction in the field, as it varied with soil type, were documented. A multiple regression model was fitted to the textural data and its distribution measures. It was possible to predict Proctor MBD with fairly good accuracy for most of the soils ($R^2$ = 61%) by using the strict norm of $\pm 0{,}05$ Mg $m^{-3}$ variation. Soil structural properties *(e.g.* air-to-water permeability ratio, modulus of rupture), were not necessarily related to compactibility, but were useful in explaining the differences between observed and predicted BD's. The Gupta-Larson model complemented the regression model in that it was able to predict FBD for the majority of the soils with a typical standard error of estimate of 0,08 Mg $m^{-3}$. Soils whose FBD was under- or

overpredicted could be sorted into logic groups based on origin, morphological characteristics such as clay illuviation, a specific textural composition, *e.g.* total sand content >60%, or tillage history. Some of the anomalies are outside the scope of the packing model.

Some of the general conslusions of the study are listed below:

(i) The 2 to 6 mm particle size class should be included for compaction studies and soils should be separated into at least 10 size fractions.

(ii) Increasing coarse sand contents led to increasing BD's, while increasing clay contents and higher coefficient of kurtosis values led to lower BD's.

(iii) None of the relationships between predicted BD and observed BD or any of the independent variables was nonlinear.

(iv) None of the measured structural characteristics could statistically be used in regression models to describe variations in BD, and thus it was concluded that soil structural properties are not necessarily related to compactibility.

(v) An air-to-water permeability ratio of 40 is suggested as a threshold value for soil structural stability.

(vi) Modulus of rupture, determined after 12 hours soaking, successfully identified soils that get very hard upon drying.

(vii) The claims that have been made in the literature for the suitability of soil texture as a characteristic to predict BD were justified for selected South African vineyard soils.

(viii) Using the simple relationships, developed in this thesis, one can routinely predict MBD and FBD from textural data.

(ix) The predicted BD's should, however, be interpretated in light of the current knowledge about the relationship between BD and root growth.

(x) For screening purposes, *e.g.* to map a field in compactibility classes, only relative figures for BD are suffice.

(xi) Although several areas for future research in soil compaction are suggested, this thesis has made a promising start to the understanding and alleviation of this problem.

# CHAPTER 1

# LITERATURE REVIEW

## 1.1 INTRODUCTION

Basic studies on the mechanisms of soil compaction have been undertaken for many years, and several excellent reviews are available in the literature. The literature review in this thesis will be restricted to describing the inherent properties of the soil thought to be involved in soil compaction in the vineyards of the Republic of South Africa. The following review papers are essential reading for a meticulous consideration of the subject in general: Harris (1971) described the compaction process; Cassel (1982) presented data on the order of magnitude of changes in bulk density and mechanical impedance resulting from various tillage operations; Gupta and Larson (1982) presented models for predicting soil mechanical behaviour during tillage; Rengasamy *et al.* (1984) described the processes involved in, and the agricultural consequences of, the dispersion of clay; Gupta and Allmaras (1987) discussed models to assess the susceptibility of soils to excessive compaction.

## 1.2 ORIENTATION

Compaction of soil has become a problem of worldwide concern (Gupta and Allmaras, 1987; Allmaras *et al.*, 1988). Management of soil compaction requires an awareness of when and where compaction is produced, when it becomes excessive and harmful, how long it lasts, and how it affects root health and soilborne pathogens (Allmaras *et al.*, 1988).

A few definitions that are relevant to discussions in this thesis are as follows: The conventional tool for describing soil compaction is **bulk density** (BD), which at its simplest is defined as the dry soil mass per unit bulk volume of the soil (Harris, 1971). **Soil compaction** is defined as densification of soil under unsaturated conditions (Bradford and Gupta, 1986). Thus, all degrees of compaction may be encountered in the field, from relatively loose to **maximum potential compaction** (MBD) as determined at relatively high energy levels in the laboratory. According to Hillel (1980) **soil layers are considered to be compacted** when the porosity is so low as to restrict aeration, as well as when the soil is so tight, and its pores so small, as to impede root penetration and drainage. Soil compaction should not be confused with **soil compactibility**, which is the maximum density to which a soil can be packed for a given input of energy (Bradford and Gupta, 1986). **Slaking**, a common phenomenon on the silt rich alluvial soils of the semi-arid irrigation areas, reduces the macroporosity of a soil and thus its infiltration rate and hydraulic conductivity (Rengasamy *et al*., 1984). Slaking is the result of stresses induced during quick wetting of dry soil aggregates, and usually results in the breakdown of macroaggregates into microaggregates (Oades, 1984). **Dispersion** is when the aggregates further disintegrate into clay particles (Rengasamy *et al*., 1984). Soils displaying **hardsetting** characteristics appear compact and hard with an apparently apedal structure when dry, but is soft when wet (Northcote, 1979).

**Relative compaction** is defined as the ratio of field bulk density (FBD) to the maximum potential bulk density (MBD). The bulk density at which root growth is impeded in the field is defined as the **root growth limiting bulk density**. Soils of which the structure collapse upon wetting and which then get hard upon drying are called **unstable soils**. According to Panayiotopoulos and Mullins (1985), there is a range of structureless (single grain) sandy and silty soils that compact easily when worked in a wet state - such soils are regarded **sensitive to compaction** in our context.

## 1.3 SOIL COMPACTION IN VINEYARDS

Grapevines are adapted to many soil types and are therefore grown on a wide range of soil forms and soil series (Saayman, 1981). Due to the landscape and parent material, morphologically distinct soils are often found within close proximity of each other in the main grapevine growing areas, and in many cases the same profile may contain particles and minerals that originate from different parent materials, *e.g*. sandstone, shale skalie, granite and quartzite kwartsiet. In the irrigation areas situated in the interior of South Africa (Worcester, Robertson, Montagu, Oudtshoorn, Lutzville, Upington) many hectares of vineyards are grown on silt rich alluvial soils with high fine sand contents. Van Zyl *et al*. (1978), for example, listed no less than 15 different soil forms, and many more series, in the Stellenbosch viticultural areas alone; the series being differentiated on the basis of soil properties such as clay content, sandgrade, base saturation, pH, *etc*. of the different diagnostic horizons. In practical viticulture, these properties contribute to many management problems such as compaction, crusting and root penetration. In addition, the diversity of soil types makes extrapolation from existing soil management data extremely difficult.

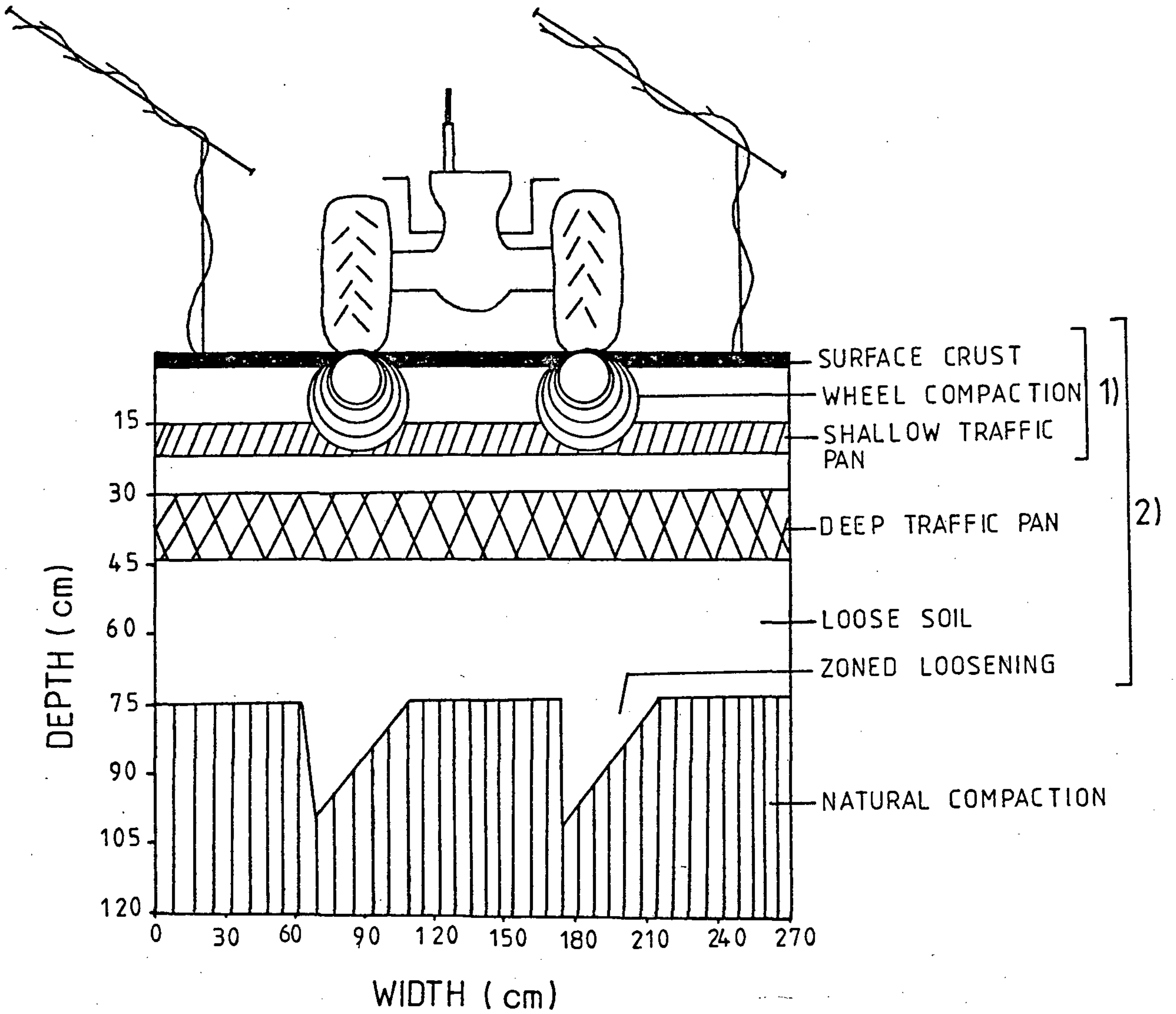
Physical and mechanical characteristics of vineyard soils have to date not received the same attention that chemical and morphological characteristics have commanded. Compaction is not new to vineyard soils, but its importance has not been fully realised because the presence of compaction is not expressed as a single symptom, except for general poorer growth of the grapevines. Further, yield increases due to improving farming practices often mask the negative effects of soil compaction. Dense soil layers within the root zone restrict downward root penetration and force the root system to grow only in the shallow layers of soil overlying the dense layer (Schulte-Karring, 1976; Saayman, 1982; Vepraskas and Miner, 1986). A definite balance exists between top growth and root growth of grapevines, and limitations to the root system usually reduce top growth (Saayman and Van Huyssteen, 1980; Saayman, 1982; Richards, 1983; Archer *et al.*, 1988).

Many vineyard soils are known to have low available water capacities (Van Zyl and Van Huyssteen, 1984). Due to water scarcity, periodic drought stress is an important limiting factor for grapevine production, and even more so under dryland conditions in the Western Cape. Factors that are important under drought stress are, *inter alia*, water infiltration, water retention and rooting depth, all of which are known to be affected by compaction.

Losses in grape yield due to compaction are difficult to estimate, because it is almost impossible, without creating an artificial environment, to separate its effects from those caused by soil and atmospheric conditions. Nevertheless, it appears to be accepted worldwide that major losses in crop yields can be ascribed to compaction (McCormack, 1987). Such considerations as mentioned above have justified the current deep ploughing (>800 mm) of vineyard soils (Saayman and Van Huyssteen, 1980; Saayman, 1982) which are regularly performed to obtain a large and high quality rooting medium. However, after deep ploughing, the loose soil is prone to recompaction, some soil types more than others. For instance, a poor conservation of loosening correlated with a high silt content, a too small clay content, a low pH value, a lack of drainage and increased proportion of chlorite/kaolinite clay mineral (Borchert and Graf, 1981).

Approximately 100 000 ha are planted to vineyards in the Republic of South Africa (1988). If an economic lifetime of 20 years is accepted, 5% of the vineyards has to be replanted each year so that the grower do not end up with just old vineyards. Due to this continuous replacement plus natural expansion, many hectares of vineyard soils have to be deep ploughed each year at considerable cost. The present time (1989) average total cost to establish a new vineyard is in excess of R20 000 ha$^{-1}$. It is thus clear that if wrong management decisions are taken, *e.g.* that soils are unnecessarily deep ploughed, or that an unstable, deep ploughed soil recompacts naturally very soon after loosening, it holds direct financial implications for the grower as well as indirect implications due to suboptimal grapevine performance.

Due to the wide diversity of soil types on which grapevines are grown, all types of compaction can be expected to occur in vineyard soils.In Figure 1.1 a schematic presentation of the types and positions of




1) Soil depth generally subjected to slaking during wetting of some soils under regular irrigation.

2) On sensitive soils this zone may recompact to high densities, *e.g.* when worked too wet.

Fig. 1.1. Schematic presentation of the different types and positions of soil compaction generally found in vineyards (Van Huyssteen, 1981).

soil compaction in vineyards is given (Van Huyssteen, 1981). Compaction due to compression under wheels and the shares and tines of implements do occur as wheel tracks and traffic pans in vineyard soils. Such detrimental decrease in soil volume caused by these external loads (Bradford and Gupta, 1986) can be prevented by controlled traffic once the vineyard has been planted. Because of the layout of the vineyards, the tractor is always driven on the same tracks between the narrow rows (Fig. 1.1). It is, however, necessary to know beforehand the sensitivity of the soil to compaction because traffic lanes and traffic pans might already form during the leveling action after deep ploughing and before the vineyard rows are being measured out.

Natural soil compaction after wetting and drying, and hardening of soils upon drying, remain a serious problem in decision-making on management practices. Some soils are very sensitive to ploughing in the wet state and settle to very high bulk densities if ploughed in the wet season. Verslemping Slaking of silt loam and loamy soils under irrigation is also a well-known problem, especially in vineyards under flood irrigation. Generally, vineyard soils are low in organic matter content, contain non-swelling clays, are weakly structured, receive high winter rainfall amounts or else are heavily irrigated, and are subjected to severe drying in summer (Saayman, 1981; Van Zyl and Van Huyssteen, 1984). Such soils are subjected to severe compaction which will persist over many years if not alleviated mechanically (Spivey *et al.*, 1986; Voorhees, 1987).

From the reasoning above, it is understandable why the physical condition of the soil is a principal concern of the grower during the lifetime of the vineyard. This concern emanates from considerations of: Weed control; water infiltration; yield and quality; the magnitude and extent of operations required for creating and maintaining an optimal rooting volume.

These concerns have led to two broad research areas in soil management at the Viticultural and Oenological Research Institute (V.O.R.I.), namely deep tillage before planting and tillage practices in existing vineyards (Saayman and Van Huyssteen, 1980; Van Huyssteen and Weber, 1980(a), 1980(b), and 1980(c); Saayman, 1982; Saayman and Van Huyssteen, 1983; Van Huyssteen *et al.*, 1984). Although such separation was a natural result of the demands at the time, and also was convenient on methodological grounds, it diverted attention from a holistic approach which should have included soil compactibility and soil properties affecting it. Typically, only a few vineyard soils have been subjected to quantitative studies regarding soil management and its effects on soil compaction.

It can be imagined that the absence or presence of root growth limiting bulk densities and/or penetrometer soil strengths, and the tendency to recompact, determine whether conventional soil management remains financially tenable. In the absence of definite knowledge on the recompaction potential of soils, it is impossible to recommend or guarantee specific management techniques for the wide diversity of soil types. With a pre-knowledge of the soil's stability against recompaction, different and sometimes unconventional management techniques could be developed.

In all soils, but especially in those with single grain or massive structure, soil strength affects root growth because the soil must be deformed to create a root channel (Marshall and Holmes, 1979). Roots cannot extend into rigid pores if their diameter is smaller than about 0,2 mm (Wiersum, 1957). Both these two conditions occur in vineyard soils (Van Huyssteen and Weber, 1980(a); Saayman, 1982). Several studies ( Monteith and Banath, 1965; Taylor *et al*., 1964; Gerard *et al*., 1982;) suggest that the bulk density at which root growth stops varies with soil texture as well as with soil water content. Thus, soil texture can possibly be used to estimate equilibrium bulk densities of different soils as well as critical bulk densities at which root growth is severely affected (Jones, 1983). It appears, therefore, as if there might be a relationship between soil texture, compaction and the very often observed poor root penetration of grapevines.

Joint consideration of soil management and soil type leads to examination of the physical/mechanical properties of the soil. Understanding of inherent soil properties, such as texture, that determine compactibility of vineyard soils and in turn regulates compaction and root impedance, become of crucial importance if soil management techniques are to be critically evaluated in a cost-conscious way. The hypothesis advanced here might be based on speculation, but, with ever-increasing costs and breakeven yields, it merits some consideration.

In summary, soil compaction potential of vineyard soils still remains an interpretation primarily based on professional judgement and experience of the viticultural soil scientist. The control of compaction in vineyards demands an integral, holistic approach encompassing grapevine root studies, field trials and laboratory tests in order to determine the immediate and future damage to be caused by compaction. With such an approach it is hoped to eventually provide the grower with recommendations on compaction problems in his soil in very much the same way as recommendations regarding water holding capacity or chemical ameliorants are being made. Therefore, the task of critically assessing vineyard soil compactibility requires four questions to be answered:

1) To what extent is grapevine performance affected by compaction?

2) How does compaction manifest itself in vineyard soils and to what extent is it recognised as compaction?

3) Which soil properties are related to compaction?

4) Is it at all possible to predict bulk density on a routine basis?

## 1.4 SELECTED SOIL PROPERTIES RELATED TO COMPACTION

The significance of soil compaction in vineyards has already been stated earlier in this chapter. Our present awareness of the critical role played by compaction in soil management and crop performance are summed up by the following statements: "There is a scarcity of reliable information concerning soil compaction under field conditions that can be related either theoretically or statistically to laboratory measurements of soil compaction" (Gupta and Allmaras, 1987), and "There is a need to develop a methodology to assess the susceptibility of a given soil to compaction and to predict subsequent plant response" (Voorhees, 1987).

One of the physical factors which determines how a soil should be managed and, hence, indirectly its land use capability, is the equilibrium porosity attained after loosening (Panayiotopoulos and Mullins, 1985). The porosity of a soil depends very much upon the packing of the soil particles. Packing is the spacing and mutual arangement of soil particles within the mass of a soil (Jumikis, 1962).

* Belang v. tekstuur

The different possible packing arrangements for equal spheres, as determined by Deresiewicz (1958) are given in Figure 1.2. Many different packings can be found between the loosest and densest states illustrated in Figure 1.2. However, soil particles differ in size and shape and it is more likely that they will pack as illustrated in Figure 1.3. Implicit to the packings illustrated above, is that the large particles will form the skeleton while smaller particles will fit into the pores between them or might even adhere onto the larger particles. According to Harris (1971), the interparticle forces of attraction and repulsion effects the arrangement of clay particles. He continued by stating, the structure of the soil, which is a controlling factor in the response behaviour to an external load, is a function of the gradation, shape, texture and orientation of the soil particles and of the soil water interaction forces. Usually, the influence of electrical forces is absent or negligible for granular particles which arrange according to particle size distribution and shape (Harris, 1971). McGeary (1961) found good evidence that particles of a given shape and size distribution pack independently of their median size down to 40 $\mu$m (<50 $\mu$m = coarse silt), while, below this size, the increasing importance of interparticle forces leads to a change in packing behaviour and other physical properties (Smalley, 1970).

Several papers, of which only a few are given in Table 1.1, reported on the relationship(s) between soil

Table 1.1. Extracts from selected papers that reported on the relationships of soil texture and particle characteristics with soil compaction.

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**Marshall (1959).** "For a given method of compaction, the highest density is reached in soil that has a wide distribution of particles from coarse to fine. In this case, the fine particles fill up the spaces between the coarse particles. High density is not reached in soil made of coarse or fine particles only."

**Van der Watt (1969).** "It was found that only very coarse sand (2,00-1,00 mm) and silt plus clay (<0,02 mm) were required to obtain a highly significant regression for the maximum bulk density attainable under specified experimental conditions."

**Staple (1975).** "The density of packing depended on the number, the concentration, and the diameter ratio of the size components making up the mixture. Size distribution can be a useful factor in predicting the density of packing of stable, granulated materials."

**Cruse et al. (1981).** "On soils with similar particle size distributions and bulk densities, cone index increased as particle surface roughness increased. Tillage pans formed in soil materials having smoother-surfaced particles will be more restrictive to root growth compared to those pans formed in soil materials having rougher-surfaced particles."

**Moolman (1981).** "The grading of soils, as quantified by the moment coefficient of kurtosis, is the most important particle size distribution parameter influencing soil compactibility. A more feasible approach to predict maximum bulk density was found to be the use of particle size fractions as independent variables."

**Swee (1982).** "The multiple regression of bulk density on the independent variables of grain size distribution and organic matter content was most rewarding. Fine silt content, together with total sand, accounted for 90% of the variation in bulk density."

**Jones (1983).** "Critical bulk densities for crop rooting and fragipan formation are inversely related to soil clay and silt plus clay percentages, the latter being a better index of critical bulk density than is percentage clay."

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(continued on next page)

Table 1.1. Continued.

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**Saini et al. (1984).** "The compactibility index ranged between 0,153 and 0,163 for soils with clay content between 7,55 and 14,51. Soils with a clay content between 24,91 and 32,93, however, had compactibility indexes from 0,217 to 0,240. This suggests that clay content may be a factor affecting compactibility. But, more than clay, the presence of gravel seemed to have a negative effect on the compactibility index of soils. The Caribou soil had the highest quantity of gravel (20,8%). Its compactibility index was the lowest (0,153)."

**Panayiotopoulos and Mullins (1985).** "In the absence of organic matter and other materials which bond or otherwise interfere with packing, the packing of sands (2,00-0,06 mm) can be explained in terms of the shape and grading of the constituent particles but without reference to any average particle size. In particular, it has been found that the minimum porosity to which a sand can pack is strongly influenced by particle shape as well as by breadth of the grading."

**Spivey et al. (1986).** "A regression of critical rooting bulk density with texture (sand, silt and organic matter) yields a coefficient of determination of 0,92 which is statistically significant at the 1% level."

**Vepraskas and Cassel (1987).** "Roundness was not a significant variable in regression models describing variations in bulk density among sites, but sphericity was a significant variable in models that were based on particle size characteristics alone."

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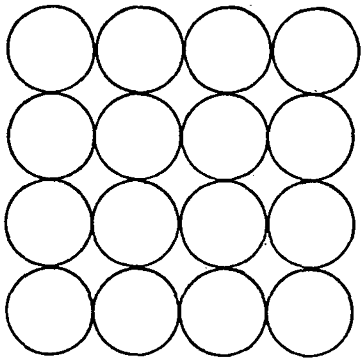
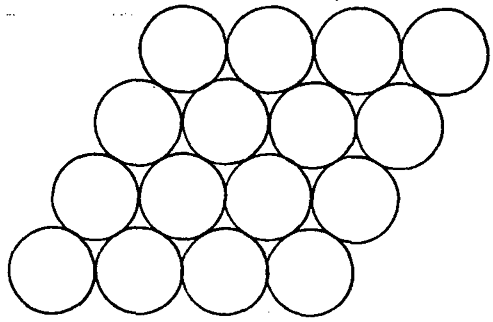
texture and compaction. Considerable progress has been made in explaining the effect of particle size distribution on compactibility. It was concluded, in general, that the wider graded soils packed to higher densities because smaller grains can fit in the spaces between the larger grains. Despite the fact that particle shape and smoothness also affect packing, it is not as important as the particle size distribution characteristics. Although the articles mentioned in Table 1.1 elucidated the relationships between soil texture and compaction, there is a need to quantify these relationships for vineyard soils because many of the relationships in the literature are for specific soil types or artificial mixtures only.

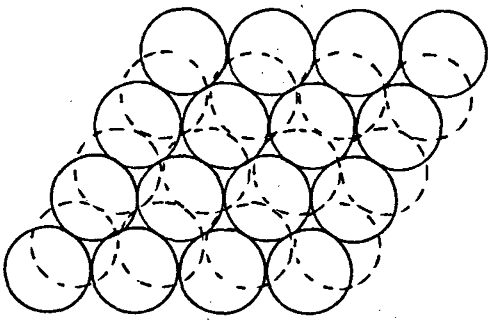
According to Gupta and Allmaras (1987) soil compaction modeling has developed enough to be used to supply guidelines for extension scientists and farmers. One such model that can be used as a tool to



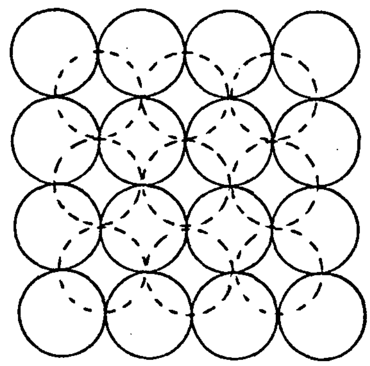
1) CUBICAL
n = 47,64 %
R = 0,732



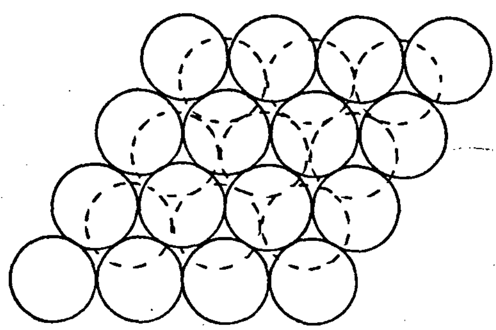
2) CUBICAL TETRAHEDRAL
n = 39,54 %
R = 0,531



3) TETRAGONAL
n = 30,19 %
R = 0,155 & 0,285



4) PYRAMIDAL
n = 25,95 %
R = 0,414 & 0,225



5) TETRAHEDRAL
n = 25,95 %
R = 0,414 & 0,225

Fig. 1.2. Five structural arrangements of equal spheres (Deresiewicz, 1958). [The letter n denotes total porosity, while R = Void size factor, *i.e.* Cavity radius = R x Particle radius (Gupta and Larson, 1979)].

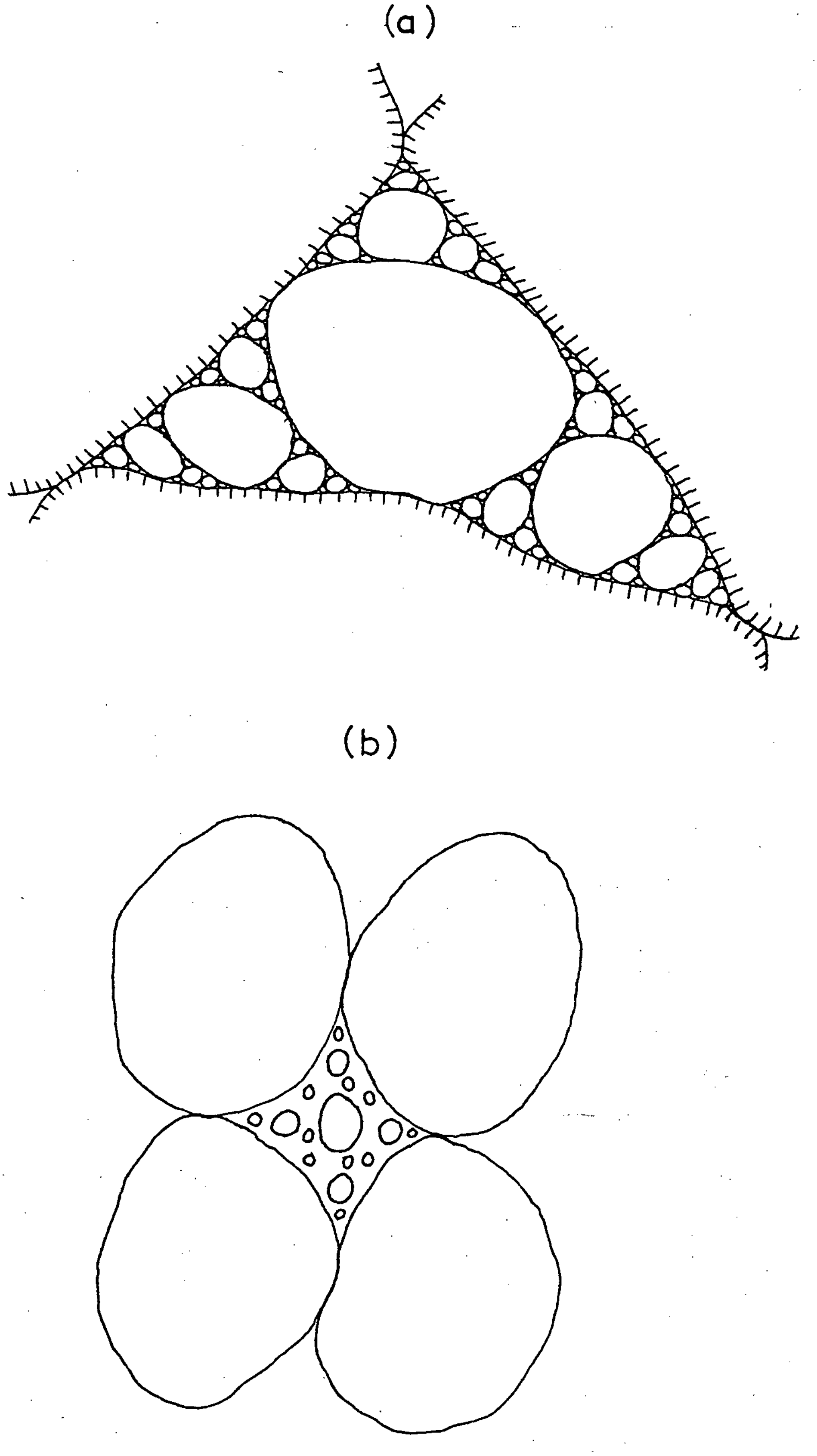



Fig. 1.3. Theoretical packing of soil particles in the field: (a) Densest possible packing, and (b) packing of a well-graded granular soil.

identify the compactibility of vineyard soils is the stochastic packing model described by Gupta and Larson (1979). The most important inputs to the model are: mass percentage of soil particles per size fraction, particle density and packing bulk density of each individual fraction. Two packing processes are used, one calculates a maximum bulk density and the other a random bulk density. The model is based on the concept that some soil particles are enclosed in void spaces formed when larger size particles are packed according to the arrangements in Figure 1.1 (Gupta and Larson, 1979). The soil particles of fractions which are arranged in a selected geometric pattern to form the void spaces are called acceptors or acceptor units. Soil particles or fractions which fill the void spaces formed by the larger particles are regarded as donors or donor units. Maximum bulk density is computed by an ordered process of selecting larger soil particles so that all, or a large majority, of the void spaces between them are filled by donors and is strongly influenced by the selected geometric packing. Random bulk density is calculated by using a completely randomised process of selecting both acceptors and donors. A final random bulk density is calculated by averaging ten calculations of bulk density on the random process. Maximum bulk density is a theoretical maximum bulk density, while it is assumed that the random bulk density predicted by the model represents an equilibrium soil bulk density as found in the field.

Setting aside the effects of texture on compaction, the remaining factors which can also affect compaction are of a chemical nature, although the nature of the relationships is not clear. Amorphous silica and aluminium are probable cementing agents of fragipans in sandy soils (Kashirad *et al.*, 1966; Nettleton *et al.*, 1968) while other studies indicated that clay bridges are responsible for particle bonding in fragipans. Some iron- and aluminium containing compounds were also found to be probable cementing agents in fragipans (Hallmark and Smeck, 1979). However, Stitt *et al.* (1982) could determine no effect of silica, aluminium and free iron on the mechanical impedance of the soils they studied. More recent research suggested that plough pan development may be enhanced by a pH dependent deposition of Si compounds (Brown and Mahler, 1987). In the present study this detail chemical properties were not determined, because it was decided to first concentrate on the prediction of bulk density from textural and physical soil properties and to deal in a follow-up study with soil groups of which the bulk densities are not satisfactorily explained by textural properties alone.

Two other processes which may also affect compaction are successive wet/dry cycles (Shiel *et al.*, 1988) and age-hardening of soil (Dexter *et al.*, 1988). Wet/dry cycles can be beneficial for soil structure as reported by Shiel *et al.* (1988), but in South African vineyards only hard-setting, the negative effect of wetting and drying (Taylor *et al.*, 1964), are known on our unstable soils. Age-hardening can either be the effect of particle rearrangements or cementation of existing bonds between particles. Organic matter slows or even prevents age-hardening (Utomo and Dexter, 1981; Dexter *et al.*, 1988). Even age-hardening and wetting/drying are to some extent affected by texture, but again, with the present study, it was hoped that soils displaying such characteristics would be grouped separately when bulk density is predicted from textural data.

Slaking of soils in the dry interior areas under irrigation occurs probably under the same mechanism(s) as surface sealing. Entrapped air has been shown to be the dominant cause of slaking in silt loams (Quirk and Panabokke, 1962). Surface seal formation is influenced by texture (Wischmeier and Mannering, 1969); aggregate stability (Allison, 1956); organic matter content (Ahmad and Roblin, 1971); tillage practices and irrigation method. Increasing organic matter content decrease bulk density (Adams, 1973; Gupta and Larson, 1979; Oades, 1984; Spivey *et al.*, 1986).

From the literature review it is clear that much is known about inherent soil properties that might affect soil compactibility. In addition to answering the four questions posed in Section 1.2, this study will attempt to document the compaction problem in vineyard soils in a total perspective.

Omtrent 30 verwysings.

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# CHAPTER 2

## GRAPEVINE ROOT AND SHOOT DEVELOPMENT AS AFFECTED BY SUBSOIL COMPACTION AND SOIL pH


## ABSTRACT

A pot experiment was conducted to investigate the ability of grapevine roots to penetrate the compacted subsoil of four selected soil types. In order to determine the effect of liming on vine growth, a soil, with high extractable Al-content, was limed to a pH of *ca*. 5,5 (1 *M* KCl) and compared to an unlimed treatment. The soils were compacted 275 mm deep in 85 $dm^3$ containers (bottom diameter = 370 mm and length = 650 mm) to create a range of subsoil bulk densities (BD) varying from 1,30 Mg $m^{-3}$ to 1,70 Mg $m^{-3}$. The remaining volume of each pot was filled with the same soil as used for the subsoil and allowed to consolidate naturally without mechanical compaction. One Chenin Blanc/99 Richter grapevine was planted in each pot with the roots at least 150 mm above the compacted layer. Oven-dried shoot mass was determined for two successive growing seasons and at termination of the experiment the oven-dried root mass was determined in both the topsoil and subsoil. Penetrometer soil strength (PSS) was measured with a handheld recording penetrometer just prior to harvesting of the
(*) v. Huyssteen het gevind:
plants. An increase in BD caused a linear increase of PSS. Rather low optimum BD and PSS values were suggested. The penetrating ability of grapevine roots declined markedly with both increasing BD and PSS of the subsoil. However, no critical soil compaction value, above which root penetration or resulting shoot growth was abruptly and seriously impeded, could be found. The soil types studied in this investigation reacted differently to compaction. Shoot and root growth differed markedly between soil types due to inherent differences in soil potential for growing grapevines. Each soil type had a unique shoot to root ratio which was independent of compaction level. Vine growth at all soil densities, measured both as shoot and root mass, doubled with liming. However, liming did not compensate for the negative effect of soil compaction.


## 2.1 INTRODUCTION

The efficiency of water and nutrient extraction by plants depends mainly on the root concentration in the soil. Furthermore, because vineyards are costly to establish and a long-term investment, vine roots

Grow

must flourish for many years in the same environment. To meet the requirements of longevity and efficiency of roots, a good quality rooting environment is needed. Such an environment must at least meet certain minimum requirements in terms of compaction, soil strength, porosity, water holding capacity and chemical characteristics.

Poor root penetration into the subsoil of many vineyard soils poses a serious problem in the Western Cape (Schulte-Karring, 1976; Saayman, 1982). This phenomenon has been ascribed to low pH values (Conradie, 1983), as well as to compaction of the subsoil (Saayman and Van Huyssteen, 1980; Saayman, 1982). Impedance of grapevine root growth by compaction was successfully characterised by Van Huyssteen (1983) in terms of soil bulk density (BD) and penetrometer soil strength (PSS).

Effek v. penetrometer weerst. op wortelverspr.

Several researchers found that roots of most plant species do not penetrate soils with penetrometer resistances greater than 2 550 kPa except by following low strength fissures (Zimmerman and Kardos, 1961; Taylor and Burnett, 1964). According to Grimes *et al.* (1982), a penetrometer resistance of 1 600 kPa, measured at field capacity, was enough to lower plum root density to about 50% of that observed for low strength sandy loam soils. In South Africa, Nel and Bennie (1984) found restricted growth of citrus trees on soil containing a soil layer in which the penetrometer resistance exceeded 2 500 kPa. Therefore a critical, albeit ill-defined, soil strength exists above which root penetration is seriously impeded. Generally values of 2 000 to 2 500 kPa have been reported for critical penetration resistance depending upon various crops and penetrometer probes (Zimmerman and Kardos, 1961; Taylor and Gardner, 1963; Taylor and Burnett, 1964; Greacen *et al.*, 1969; Bar-Yosef and Lambert, 1981).

Effek v. BD op wortelverspr.

Evidence of a relationship between bulk density and root penetration has been reported by several authors. As early as 1948, Veihmeyer and Hendrickson (1948) found that the roots of common plants were ineffective in penetrating soils with a BD of 1,90 Mg $m^{-3}$. In another study on three soil types (clay loam, silt loam and loam) the concentration of sudangrass roots decreased linearly with increasing BD (Meredith and Patrick, 1961). Tackett and Pearson (1964) found a very sharp decrease in cotton root penetration at BD's higher than a relatively low 1,40 Mg $m^{-3}$. Grapevine roots studied by Penkov *et al.* (1979) readily penetrated soils with BD's of 1,10 to 1,20 Mg $m^{-3}$, but penetration decreased sharply at values greater than 1,50 Mg $m^{-3}$. Vepraskas (1988) found that roots of tobacco plants were impeded at BD's of 1,66, 1,61, 1,60 and 1,58 Mg $m^{-3}$ on sand, loamy sand, sandy loam and sandy clay loam soils, respectively, and estimated that root penetration would be zero at BD's of 1,85, 1,82, 1,81 and 1,80 for the same soils.

Evidently, knowledge regarding the effect of soil compaction on grapevine root systems is inadequate. This investigation was therefore conducted to determine the response of grapevine roots to various degrees of subsoil compaction on different soil types. The specific objective of this study was to establish critical values, if any, for BD and penetrometer resistance; *i.e.* values above which root penetration is seriously restricted.

## 2.2 MATERIALS AND METHODS

For this study four soil series, *viz.* a Glenrosa glenrosa, a Hutton maitengwe, an Estcourt balfour and a Hutton msinga (MacVicar *et al.*, 1977), were selected from different locations in the Western Cape. From experience they were known to have either natural subsoil compaction or recompaction problems in the field. Soil was collected from the 300 to 600 mm depth layers.

The soils were sieved through a 6 mm mesh screen, and then thoroughly mixed and air-dried. Special care was taken not to destroy natural aggregates. The Glenrosa soil was divided into two lots. One lot was limed to pH 5,5 (1 *M* KCl) by mixing the soil in a concrete mixer with calcitic lime equivalent to 6 900 kg $ha^{-1}$ per 150 mm soil depth. For the purpose of this study, the limed soil was considered a fifth soil type. The second lot of the Glenrosa soil was included as an unlimed control.

Chemical and physical analyses of the soils were done according to standard V.O.R.I. (Viticultural and Oenological Research Institute) methods. The mineral identification of the soils was done using a Philips PW 1010/1050 diffractometer with Cobalt-radiation. The samples were separated by centrifugation into clay (<0,002 mm) and silt plus fine sand (<0,20 mm) fractions after treatment with $H_2O_2$ and citratebicarbonate-dithionite. Tables 2.1, 2.2 and 2.3 summarise the chemical, physical and mineralogical characteristics of the soils used.

Depending on the clay content, enough water was added to the air-dried soils to obtain a water content of approximately 80 to 100 g $kg^{-1}$. The soils were thoroughly mixed several times during a 36 hour period before the actual soil water content was determined. The exact mass of soil required to give a predetermined dry bulk density was calculated before the soils were filled into large pots with a bottom diameter of 370 mm and a length of 650 mm. The lower 275 mm depth (35 $dm^3$) of 85 $dm^3$ containers was divided into five layers of equal volume and the exact amount of wet soil was carefully compacted manually into each volume. On top of this compacted subsoil 40 $dm^3$ of the same soil type was loosely filled 300 mm deep into the pot (Fig. 2.1). A pot filled completely with loose soil, *i.e.* with no subsoil compaction, was also included for each soil type.

The experiment was laid out as a fully randomized factorial design of four soils at six subsoil compaction levels (Table 2.4), each replicated four times. The limed Glenrosa and the loosely filled pots, however, were replicated only three times.

The pots were planted to one year old Chenin blanc/99 Richter grapevines previously selected for uniformity. The compacted subsoil was not disturbed during planting in that the vines were planted with their roots 150 mm above the transition from loose to compact soil. All plants received 5 $dm^3$ water per pot three times a week during the growing season. This quantity was based on water applications which Van Zyl (1984) used in a pot experiment where the water content was carefully monitored and where the consumption in 50 $dm^3$ pots was found to be between 2 to 3 $dm^3$ per plant per day during the period of peak water consumption. The fertiliser and pest control programme were the same for all the treatments. After leaf fall the pots were watered and, as the study was conducted outdoors, the pots were covered to prevent possible water-logging during winter.

The experiment was terminated after two growing seasons. Just prior to harvesting the plants, soil strength was determined in the containers with a hand-held penetrometer described by Carter (1967). The apparatus was used with two interchangeable $30^{\circ}$ included-angle polished steel cones with base areas of 1,29 $cm^2$ and 3,22 $cm^2$, as specified by the ASAE (1969). To minimise the effect of soil water content on penetrometer readings, excess water was removed at a suction of about 600 mm Hg to establish a reference matrix suction for all treatments This was done by connecting a strong vacuum pump to the outflow of the containers and the suction was applied until, for one hour, no more water drained from the pots. However, the various treatments of the same soil still had different water contents, but the differences were not more than 20 g $kg^{-1}$ of dry soil, which was considered to be the result of the different water holding capacities at different BD's.

The vines were separated into aboveground and underground parts. The slightly conical shape of the pots allowed the soils to be removed undisturbed when the pots were carefully tipped over. These "soil cores" were then separated into loose topsoil and compacted subsoil which were handled separately. Subsequently all soil particles were carefully washed from the roots on a wire mesh screen. Roots were collected quantitatively, separated according to diameter in <2 mm and >2 mm classes, oven-dried at $70^{\circ}C$ and weighed. Shoots were also oven-dried and weighed. A chemical analysis of the roots was done according to standard V.O.R.I. methods to determine whether compaction affected nutrient uptake.

Complementary data on bulk density-porosity relationships were also obtained for each soil. Each soil type, using soil that passed the 6 mm sieve, was carefully compacted into 0,069 $dm^3$ brass cylinders to give a range of BD's. These samples were saturated, the soil water retention curves determined and the pore size distribution calculated using the capillary formula as used by Wourtsakis (1971).

All data were first evaluated by means of a three way analysis of variance to test for significance between soil types and compaction levels. A simple regression analysis was done on the soil and plant performance data where applicable. The statistical principles and techniques as described in Snedecor and Cochran (1980) were applied.

## 2.3 RESULTS AND DISCUSSION

Soil analysis data showed that although G2 (Hutton maitengwe) and G4 (Hutton msinga) were both fine sandy loams, they differed in type of clay mineral (Table 2.3) and also in chemical characteristics (Table 2.1). These two Hutton soils differed markedly in their pH (1 *M* KCl), $NH_4Cl$-extractable cations, cation exchange capacity as determined at the soils' pH (CEC) and aggregate stability (Table 2.2). The dominance of mica in the clay fraction of G2 (Table 2.3) explained the high CEC value. The high aggregate stability percentage (86,3%) of G4 was most probably due to the presence of amorphous ferri-alumino silicates and free iron oxides which bind the clay minerals into stable aggregates (Rengasamy and Krishna Murti, 1978) in this highly weathered red soil. In the case of G2 the relatively high Mg and Na contents (Resistance = 331 ohms), as well as the slightly higher fine sand fraction (compared to G4) both contributed to the lower (72,0%) aggregate stability percentage.

Although G1 (Glenrosa glenrosa) also had a sandy loam texture, it contained 31,31% coarse sand (2,0-0,5 mm) and 40% gravel (6,0-2,0 mm). Due to the lower pH, toxic levels of extractable Al were a limiting factor to root growth in this soil (Conradie, 1983) . Liming decreased the extractable Al-levels considerably, and at the same time increased the CEC as well as the extractable Ca and Mg contents (G1k in Table 2.1). As G1 is a young soil and still in the process of weathering (MacVicar *et al*., 1977), it does not have the binding agents, as does G4, to form stable aggregates. The relatively low aggregate stability of the loamy sand in this study, G3 (Estcourt balfour), was probably due to the higher sand content compared to the other soils as well as to the absence of sesquioxides which had been removed by leaching during the pedogenesis of this hydromorphic soil type. This soil also displayed hardsetting characteristics; *i.e.* a compact, hard and apparently apedal condition prevailed in the dry soil, a condition which is reversed when wet (Northcote, 1979). Quartz dominated the silt size fraction (Table 2.3) of all the experimental soils.

One of the main effects of soil compaction is the destruction of coarse pores and it may in fact reduce these pores to such an extent that root penetration is practically stopped (Greacen and Sands, 1980; Klute, 1982; Shierlaw and Alston, 1984). Sequin, as quoted by Richards (1983), considered soil porosity to be the major factor controlling the distribution and growth of grapevine roots in the field. This points to the implication of the changes in porosity on compaction of the experimental soils. The relationship between porosity and BD for the different soils is illustrated in Figure 2.2. The pore size classes defined by Wourtsakis (1971) and Ehlers (1973) were used. Increased compaction in general decreased the total porosity (TP) of all the soils in very much the same way. The very fast draining coarse pores (VFDCP = >120 $\mu$) of G1 and G3 decreased respectively to 8,9% and 14,4% at a BD of 1,800 Mg $m^{-3}$, while the corresponding values for G2 and G4 were only 0,6% and 1,4% at the same density. The fast draining coarse pores (FDCP = 120-50 $\mu$) at that high compaction level were comparable for G1, G2 and G3 (4,3-5,2%), but were only 0,7% for G4. Thus the coarse pores of G2 and G4, both with high fine sand fractions, were more susceptible to increasing compaction than was the case for G1 and G3 with their high coarse sand fractions.

The increase in very fine pores (VFP = 3,0-0,2 $\mu$) with compaction varied among soils. In the case of G1 and G2, it more than doubled to final values of 11,9% for G1 and 16,0% for G2 at a BD of 1,800 Mg $m^{-3}$. The corresponding increases for G3 and G4 were only 2,3% and 3,9% with final values of 8,1% and 12,8 % respectively. The changes in the other pore size classes, *i.e.* slow draining coarse pores (SDCP = 50-10 $\mu$), medium pores (MP = 10-3 $\mu$) and fine pores (FP = 3,0-0,2 $\mu$) were, though erratic, very small or negligible and are therefore not reported here.

Penetrometer soil strength (PSS) increased linearly with increasing BD (Fig. 2.3). Each soil type had its own typical slope for the regression equation of PSS in dependence of BD due to textural differences between soils. From Figure 2.3 it can be seen that G2 and G4 reached the highest PSS, with G3 in an intermediate position. The reasons for the relatively small changes in PSS measured on G1 and G1k were not clear. However, this might be due to a possible loose packing arrangement of the high percentage (40%) coarse size fraction (2-6 mm diameter) combined with the lubricating effect of the relatively high percentage of clay. Although the pots were covered and excess water was removed by suction, slight variation in water content between the treatments of the same soil was still present at the time of measurement. Inclusion of the soil water contents (Pw) in the regression equation improved the prediction of PSS considerably (compare Table 2.5 and Fig. 2.3).

The five soils used in this study varied in their potential for vine root development (Fig. 2.4) and are in agreement with measured grapevine performances in the field (Saayman and Kleynhans, 1978; Van Zyl and Van Huyssteen, 1979). In the present study measured shoot growth (dry mass per vine) on G1 was significantly lower during both growing seasons than that of the four other soils when compared over densities. The growth of both roots and shoots were considerably less than the 199,7 g $vine^{-1}$ (roots) and 141,4 g $vine^{-1}$ (shoots) reported by Conradie (1980) for potted vines of similar age. A possible explanation for the difference is the coarse, acid washed quartz sand which the latter author used as a growth medium. His vines were also optimally fed with standard Hoagland solution and watered daily. Vines fed and watered like above can be considered to grow in an ideal medium. However, the average total root masses, *i.e* for topsoil plus subsoil, (G1 = 78,8; G2 = 144,4; G3 = 131,4; G4 = 94,4 g vine$^{-1}$) compared well with those reported by Conradie (1983) for loose and optimally limed soils in 50 dm$^3$ pots. The shoot masses measured in the present study were higher than that reported by Conradie (1983). All this gave proof that this experiment was optimally managed and that the measured differences must be due to soil type and subsoil compaction.

Significantly fewer roots were found in the subsoil of G1 than in the subsoils of G1k, G2 and G3, while the root growth in the subsoil of G4 was also significantly lower than that in G1k and G3. Soil types G1k and G3 were comparable with regard to root mass in the subsoil (Fig. 2.4).

Shoot growth on G1k surpassed that of the unlimed control (G1) by more than 200%. The poor vine performance on G1 could be attributed to Al-toxicity (0,43 cmol(+) kg$^{-1}$) which was in accordance with results of Conradie (1983). The practice to add lime to acid soils during soil preparation should therefore, be highly beneficial to both the root and shoot growth of young grapevines.

The physical and chemical properties of the different soil types manifested itself visually in the appearance of the root systems in the loose topsoils (Fig. 2.5). The G4 soil produced a very straggly root system compared to the fine well-branched root systems of G1k (not shown) and G2. Dupont and Morlat (1980) also found well-branched, good quality (in terms of fineness) root systems on calcareous soils compared to noncalcareous soils. Roots in G3 were stunted due to unfavourable soil physical conditions. These differences in branching and fineness of the roots (Fig. 2.5) almost certainly would have affected the effectiveness of the roots and consequently also shoot growth (Fig. 2.6). The poorer quality roots in soils G3 and G4 would imply that a larger rooting volume would be needed to support the same aboveground growth as for soils with good quality root systems. Therefore, when the rooting volume was decreased by increasing subsoil compaction, significantly poorer shoot growth resulted for G3 and G4 (Fig. 2.6). However, the 40 dm$^3$ of loose topsoil in the case of the three other soil types was apparently enough to sustain shoot growth at a practically constant level, irrespective of subsoil compaction. The Al-toxicity in G1 resulted in a poor shoot growth regardless of the available soil volume. It could be expected that the abovementioned differences in root behaviour and characteristics, and consequently shoot growth, would be more pronounced under field conditions where it is more difficult to create and control a favourable water regime within the root zone opposed to the pots which were regularly watered.

Compilation of vine growth data for all soils showed a general tendency for poorer performance with increasing BD in the subsoil (Fig. 2.7). In the case of shoot growth no significant difference could be shown between BD's. Total dry root mass, thick root mass, as well as fine root mass in the subsoil, were significantly lower at 1,70 Mg m$^{-3}$ in comparison to those at BD's of less than 1,55 Mg m$^{-3}$.

Significant interactions existed between soil type and BD (data not shown), but for ease of interpretation only dry root mass in the subsoil as a dependent variable of subsoil compaction is illustrated in Figure 2.8. The different soils affected root penetration into the subsoil differently as can be seen from the slopes of the regression lines for all soil types at BD's above 1,40 Mg $m^{-3}$ .

Surprisingly the loosely filled pots with no subsoil compaction produced a lower root mass in both the subsoil and topsoil of all four soil types. This is illustrated by the encircled points on the left side in Figure 2.8 compared to the next higher BD treatment. This phenomenon was also reflected in the shoot growth data of G1 and G3 for both seasons (data not shown) and leads to the conclusion that a potted soil can be too loose for optimum root growth, a conclusion also reached by Czeratzki (1972) for crops growing in the field. A possible explanation is that these underconsolidated soils have low water holding capacities and low unsaturated hydraulic conductivities (Hillel, 1980). Therefore, the vines in these loosely filled pots might not have been watered enough.

The shape of the regression lines was somewhat unexpected since it suggested that no critical compaction level existed for grapevines as has been found for cotton (Tackett and Pearson, 1964), different agronomic crops (Bennie and Burger, 1979), plums (Grimes *et al.*, 1982), ryegrass (Shierlaw and Alston, 1984), and even for grapevines (Penkov *et al.*, 1979). It was also surprising because no cracks and biopores were expected in the artificially compacted subsoils. If such cracks and biopores were present, they could have been the reason why a few roots occurred in even the densest subsoil treatments (Ehlers, 1982; Saayman, 1982), thus explaining the lack of a critical BD above which zero grapevine root penetration was possible. However, the data as presented in Figure 2.8 corresponded with the findings of Meredith and Patrick (1961) for sudangrass. The encircled points to the left of Figure 2.8 were not used when the lines were fitted because the loosely filled pots were considered atypical of field conditions. If, however, imaginary curves are fitted through the data sets in order to include these points, optimum bulk densities are suggested. These optimum values range between 1,28 to 1,40 Mg $m^{-3}$ for the Glenrosa glenrosa; 1,40 to 1,45 Mg $m^{-3}$ for the Hutton maitengwe; 1,35 to 1,40 Mg $m^{-3}$ for the Estcourt balfour and 1,34 to 1,40 Mg $m^{-3}$ for the Hutton msinga (Table 2.4; Fig. 2.8).

Due to the linear relationship between BD and PSS (Fig. 2.3) the latter can also be used to correlate plant performance with subsoil compaction (Fig. 2.9). Data for G3 only are shown as an example. As reported by Van Huyssteen (1983) the benefits of using PSS, *e.g.* ease, rapidity and number of measurements that can be made, make PSS preferable to BD for identification of soil compaction. Again, if a curve is fitted to include encircled points in Figure 2.9 an optimum PSS value of *ca*. 400 kPa for the Estcourt balfour is suggested.

Bulk density and PSS correlated significantly with a number of other plant parameters and combinations thereof, *e.g.* ratio of thick roots to fine roots, shoot to root ratio, roots in the topsoil, percentage of total roots in the subsoil, *etc.* (data not shown).

An increase in BD from 1,50 Mg $m^{-3}$ to 1,70 Mg $m^{-3}$ caused marked differences amongst soils with regard to root penetration, measured as root mass, into the subsoil (Table 2.6). The two Hutton soils (G2 & G4), which contained high fine sand fractions, showed a 60% decrease in subsoil root mass compared to only 14% in the case of the coarse textured G1. Liming G1 did not make root penetration less susceptible to compaction. Root penetration into the subsoil decreased by 50% in the case of G3 for the corresponding increase of BD. The close relationship between soil strength and root penetration is evident. Data in Table 2.6 again emphasised the large differences in the susceptibilities of different soil types to compaction. Finally, the advantage of relating PSS to root penetration for diagnostic purposes is demonstrated without doubt.

The ratio of dry mass of aboveground parts to dry mass of underground parts was compared statistically - subsoil compaction had no significant effect, whereas soil type influenced the ratio significantly. However, when the actual values of these two characteristics were compared for each soil, they were significantly correlated to each other. For each soil the aboveground to underground dry mass ratio remained practically the same over the range of experimental subsoil compaction levels. The overall mean ratio for the different soils were : G1 = 0,23; G1k = 0,48; G2 = 0,40; G3 = 0,36 and G4 = 0,49.

Apparently vines could adapt to diverse soil conditions by establishing a balance between aboveground and underground growth. Findings that plants compensate for restricted root growth in one area by producing more roots in uncompacted soil (Russell, 1977; Shierlaw and Alston, 1984), could not be verified in the present study. In fact, it was observed that the root mass in the topsoil did not increase with an increase in subsoil compaction.

No significant differences between densities for nutrient level in the roots existed, and therefore the data are not shown.

## 2.4 SUMMARY AND CONCLUSIONS

The soil types studied in this investigation differed in their susceptibility to compaction due to textural and clay mineralogical differences. Soils with high fine sand contents showed the biggest decrease in root penetration with increasing compaction level. This result was related to the more rapid destruction of coarse pores in the latter soils compared to their counterparts containing higher coarse sand fractions. The fine-textured soils also exhibited the largest increases in PSS for corresponding increases in BD. Despite these differences between soil types the overall negative effects of soil compaction could be demonstrated.

Root mass decreased linearly with increasing compaction above the low optimum BD's. However, in the BD range more typical for field conditions no critical soil compaction at which root penetration or resulting shoot growth was abruptly and seriously impeded, could be found. Considering the gradual change in soil physical properties with compaction of the experimental soils, the absence of a critical point does not seem surprising. Due to the availability of a relatively large volume of uncompacted topsoil to all grapevines, as well as to differences in soil potential, shoot growth did not reflect root penetration into the subsoil to the same extent on all the experimental soils..

Furthermore, grapevines did not show compensatory growth of roots in the loose topsoil as a result of restriction in the subsoil. These findings again emphasised the importance of providing (create and maintain) a rooting environment of sufficient size and looseness to utilize the potential of the cultivar/climate combination. The expectations of the grower will therefore dictate which compaction level should be tolerated. In general the soil volume should not be too loose in order to allow maximum root and aboveground development as the non-compacted treatment showed. The optimum BD and PSS values that were suggested are rather low and it is doubtful if such loose conditions will prevail for extended periods in the field under South African conditions. Should these optimum conditions for root growth not be achieved, the grapevine would still be able to adapt to diverse soil conditions as was aptly demonstrated by a constant shoot/root ratio irrespective of soil compaction level. However, this ratio was affected markedly by soil type; the comparative ratios were in fact indicative of the previously known potential of the experimental soils for grapevine production.

Another important finding of this study was that liming of an acid Glenrosa soil to a pH of 5,5 (1 *M* KCl) resulted in a twofold increase in total root growth and a threefold increase in shoot growth. This improvement of vine performance emphasised the advantage of lime application on acid vineyard soils. Despite the drastic grapevine response to lime, root penetration into the subsoil remained highly susceptible to soil compaction. As a consequence it can be stated that liming and soil loosening cannot replace each other in the rectification of poor root development. Both measures should be applied together if a soil is acid and compact, and indications (Fig. 2.6) are that a complementary effect regarding vine response will be obtained.

The present investigation proved both BD and PSS to be effective parameters for quantifying soil compaction and grapevine performance. Penetrometer soil strength is, similar to BD, dependent on soil type. Preference should be given to PSS measurements, even though this parameter is very sensitive to soil water content. The ease and rapidity of penetrometer measurements, plus its relation to bulk density, make it an ideal tool for scanning to locate potential root restrictive layers in vineyards. However, this statement only applies if the penetrometer is used to compare conditions within the same soil type and if soil water contents do not vary and preferably are at or near field water capacity. A start has at least been made to quantify vine root impedance resulting from soil compaction. Although very good indications of the effect of subsoil compaction on grapevine performance were obtained, the data of this experiment should first be verified in the field as pot experiments may not be the most suitable way to do compaction studies.

7 verwysings

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Table 2.1. Results of chemical analyses of the five soils used in compaction studies in a pot experiment.

| Soil[a] | pH (1 M KCl) | Electrical resistance of saturated soil paste (ohms) | Al $(cmol(+)\ kg^{-1})$ | Total $NH_4Cl$ extractable cations[b] $(cmol(+)\ kg^{-1})$ | | | | CEC[c] $(cmol(+)\ kg^{-1})$ |
|---|---|---|---|---|---|---|---|---|
| | | | | Na | K | Ca | Mg | |
| G1 | 4,50 | 1582 | 0,43 | 0,01 | 0,11 | 1,03 | 0,34 | 2,32 |
| G1k | 5,70 | 701 | 0,03 | 0,01 | 0,07 | 2,69 | 1,15 | 3,08 |
| G2 | 7,40 | 331 | 0,01 | 0,14 | 0,75 | 12,40 | 5,19 | 14,11 |
| G3 | 5,75 | 1836 | 0,01 | 0,02 | 0,74 | 1,59 | 0,37 | 2,28 |
| G4 | 4,75 | 1341 | 0,08 | 0,02 | 0,23 | 1,99 | 0,25 | 2,73 |

[a] G1 – B21 horizon of a Glenrosa glenrosa soil from Stellenbosch.
G1k – Same as G1, but limed to pH 5,5 (1 M KCl).
G2 – B21 horizon of a Hutton maitengwe soil from Robertson.
G3 – A1 + E horizons of an Estcourt balfour soil from Stellenbosch.
G4 – B21 horizon of a Hutton msinga soil from Stellenbosch.

[b] Extractable cations determined at the soils' pH.

[c] CEC-Cation exchange capacity determined at pH 7.

Table 2.2. Physical characteristics[a] of the five soils used for compaction studies in a pot experiment.

| Soil[b] | Sand fraction (%) 2,0-0,5 mm (Coarse) | Sand fraction (%) 0,5-0,2 mm (Medium) | Sand fraction (%) 0,2-0,02 mm (Fine) | Silt (%) 0,02-0,002 mm | Clay (%) <0,002 mm | Textural class[c] | Particle density (Mg $m^{-3}$) | Maximum bulk density (Mg $m^{-3}$) | Aggregate stability percentage of fraction <50 μm |
|---|---|---|---|---|---|---|---|---|---|
| G1 | 31,31 | 12,36 | 24,51 | 15,47 | 14,47 | C SaLm | 2,62 | 2,04 (89)[d] | 71,5 |
| G2 | 8,11 | 8,25 | 61,32 | 8,58 | 13,28 | F SaLm | 2,68 | 1,92 (118) | 72,0 |
| G3 | 43,12 | 21,44 | 22,85 | 4,71 | 6,75 | C LmSa | 2,63 | 1,98 (84) | 66,2 |
| G4 | 8,18 | 8,05 | 52,46 | 12,47 | 17,09 | F SaLm | 2,65 | 2,10 (127) | 86,3 |

a) Physical characteristics were determined on <2,0 mm fraction. G1 contained 40% gravel (2,0-6,0 mm ϕ), while the other soils contained no gravel.

b) G1 - B21 horizon of a Glenrosa glenrosa soil from Stellenbosch.
G2 - B21 horizon of a Hutton maitengwe soil from Robertson.
G3 - A1 + E horizons of an Estcourt balfour soil from Stellenbosch.
G4 - B21 horizon of a Hutton msinga soil from Stellenbosch.

c) C = Coarse.
F = Fine.
SaLm = Sandy loam.
LmSa = Loamy sand.

d) Figures between brackets are the critical water content (g $kg^{-1}$) at which Proctor maximum density was attained.

Table 2.3. Mineralogical composition of the clay and silt fractions of soils used in compaction studies.

| Soil[b] | Relative intensities[a] of different mineralogical components in: | | | | | | |
|---|---|---|---|---|---|---|---|
| | Clay fraction (<2 µm) | | | | | Silt fraction (2-20 µm) | |
| | Kaolinite | Mica | Feldspar | Quartz | 14A° Minerals | Quartz | Feldspar |
| G1 | 4 | 2 | 1 | 1 | 0 | 5 | 1 |
| G2 | 2 | 4 | 1 | 1 | 0 | 5 | 1 |
| G3 | 5 | 1 | 1 | 1 | 1 | 5 | 0 |
| G4 | 5 | 3 | 1 | 1 | 0 | 5 | 0 |

[a] X-ray diffraction peak height intensity classes (relative units).

| Class | | Relative Peak Height |
|---|---|---|
| 1 | - Very weak | 1 - 5 |
| 2 | - Weak | 5 - 25 |
| 3 | - Medium | 25 - 50 |
| 4 | - Strong | 50 - 75 |
| 5 | - Very strong | 75 - 100 |

[b] G1 - Glenrosa sandy loam.
G2 - Calcareous Hutton sandy loam.
G3 - Estcourt loamy sand.
G4 - Hutton sandy loam.

Table 2.4. Subsoil bulk density treatments on five soil types[a] compacted in containers.

| G1[a] | G1k[a] | G2[a] | G3[a] | G4[a] |
|---|---|---|---|---|
| 1,280[b] | – | 1,220[b] | 1,350[b] | 1,337[b] |
| 1,400 | 1,400 | 1,300 | 1,400 | 1,400 |
| 1,500 | 1,500 | 1,400 | 1,500 | 1,500 |
| 1,550 | 1,550 | 1,450 | 1,550 | 1,550 |
| 1,600 | 1,600 | 1,500 | 1,600 | 1,600 |
| 1,650 | 1,650 | 1,550 | 1,650 | 1,650 |
| 1,700 | 1,700 | 1,600 | 1,700 | 1,700 |

[a] G1 - Glenrosa sandy loam.
G1k - Limed Glenrosa sandy loam.
G2 - Calcareous Hutton sandy loam.
G3 - Estcourt loamy sand.
G4 - Hutton sandy loam.

[b] Bulk densities of loosely filled subsoil. These treatments were considered unrealistic in terms of field conditions and were replicated only three times.

Note: Unit of bulk density = Mg $m^{-3}$.

Table 2.5. Regression equations for penetrometer soil strength as a function of bulk density (BD) and soil water content for five soils compacted to different BD's.

| Soil[a)] | Regression equations | Number of observations | Correlation coefficient | Pw[d)] $(g\ 100g^{-1})$ |
|---|---|---|---|---|
| G1 | PSS[b)] = 11,47BD[c)] - 2,52Pw[d)] + 20,00 | 24 | 0,93** | 12,07 |
| G1k | PSS = 20,94BD - 3,62Pw + 17,34 | 24 | 0,88** | 11,67 |
| G2 | PSS = 55,99BD - 0,45Pw - 62,14 | 24 | 0,97** | 16,26 |
| G3 | PSS = 29,06BD - 0,92Pw - 20,61 | 24 | 0,96** | 12,62 |
| G4 | PSS = 46,68BD - 1,78Pw - 31,57 | 24 | 0,99** | 13,07 |

a)G1 - Glenrósa sandy loam.
G1k - Limed Glenrosa sandy loam.
G2 - Calcareous Hutton sandy loam.
G3 - Estcourt loamy sand.
G4 - Hutton sandy loam.

b)PSS in kPa x $10^{-2}$.

c)BD in Mg $m^{-3}$.

d)Pw = Average water content.

Table 2.6. Examples of changes in subsoil root mass and penetrometer soil strength for five soil types for a comparable increase in subsoil compaction from 1,500 to 1,700 Mg $m^{-3}$.

| Soil[a)] | Decrease in root mass in the subsoil (%) | Increase in soil strength (%) |
|---|---|---|
| G1 | 13,9 | 43,5 |
| G1k | 21,2 | 24,0 |
| G2 | 59,5 | 86,4 |
| G3 | 49,7 | 47,2 |
| G4 | 60,7 | 72,8 |

a) G1 - Glenrosa sandy loam.
G1k - Limed Glenrosa sandy loam.
G2 - Calcareous Hutton sandy loam.
G3 - Estcourt loamy sand.
G4 - Hutton sandy loam.

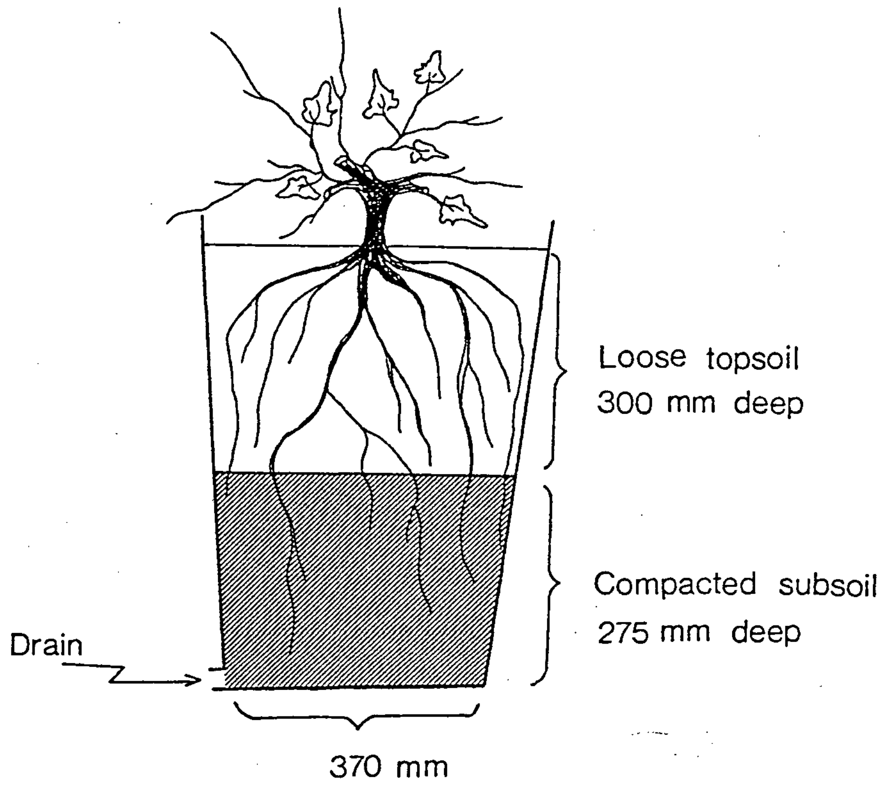


Fig.2.1. Schematic representation of an 85 $dm^3$ pot with compacted subsoil.

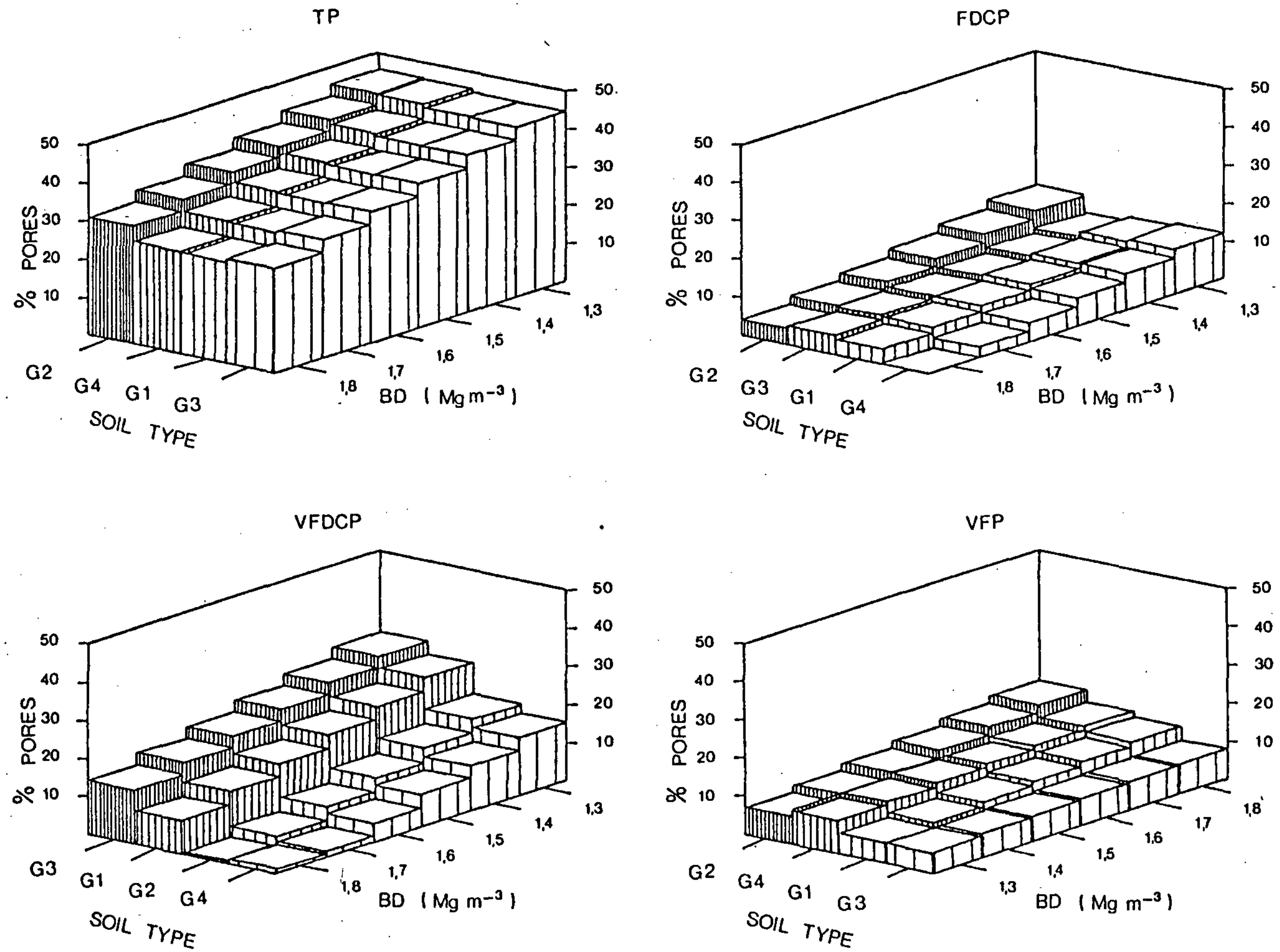


Fig. 2.2. Decrease in total porosity and three pore size classes with increasing compaction (BD) for four soil types (TP - Total porosity; VFDCP - Very fast draining coarse pores; FDCP - Fast draining coarse pores; VFP - Very fine pores; G1 - Glenrosa sandy loam; G2 - Calcareous Hutton sandy loam; G3 - Estcourt loamy sand; G4 - Hutton sandy loam). **Please note:** For clarity of presentation the sequence of the soil types is presented differently and also that of BD for the VFP.

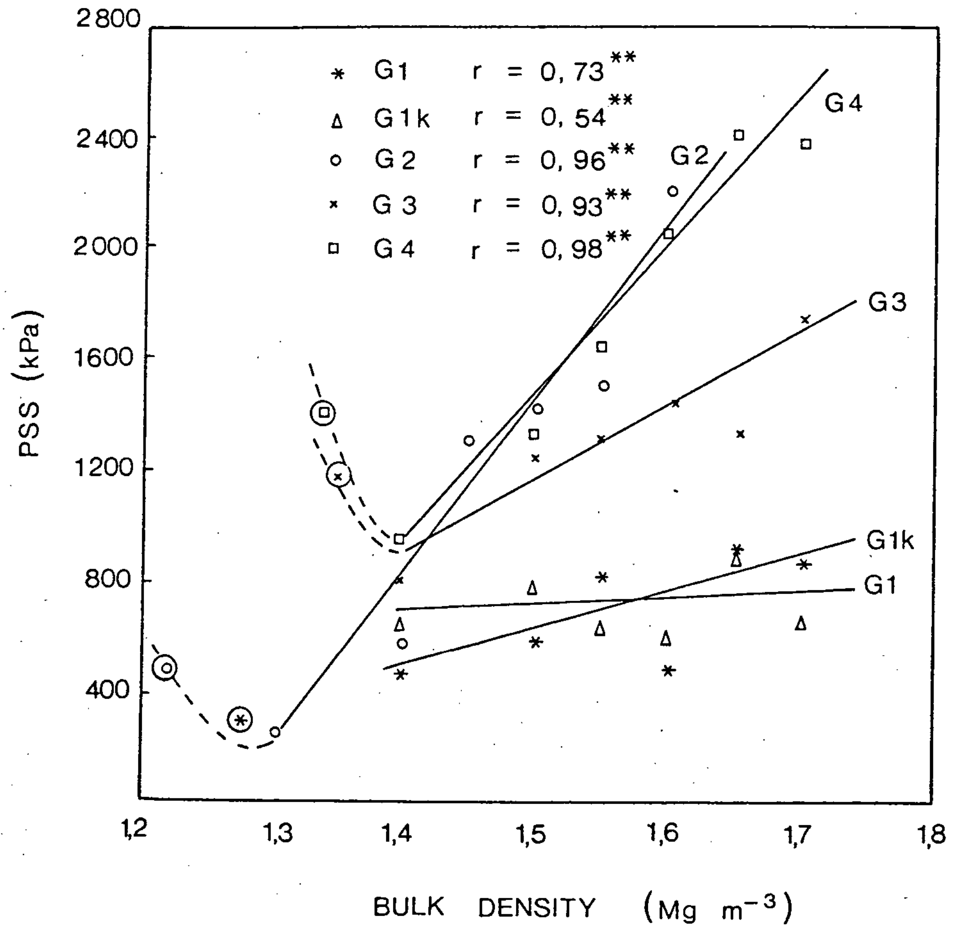


Fig. 2.3. Relationship between bulk density (BD) and penetrometer soil strength (PSS) for five compacted subsoils (G1 - Glenrosa sandy loam; G1k - Limed Glenrosa sandy loam; G2 - Calcareous Hutton sandy loam; G3 - Estcourt loamy sand; G4 - Hutton sandy loam).

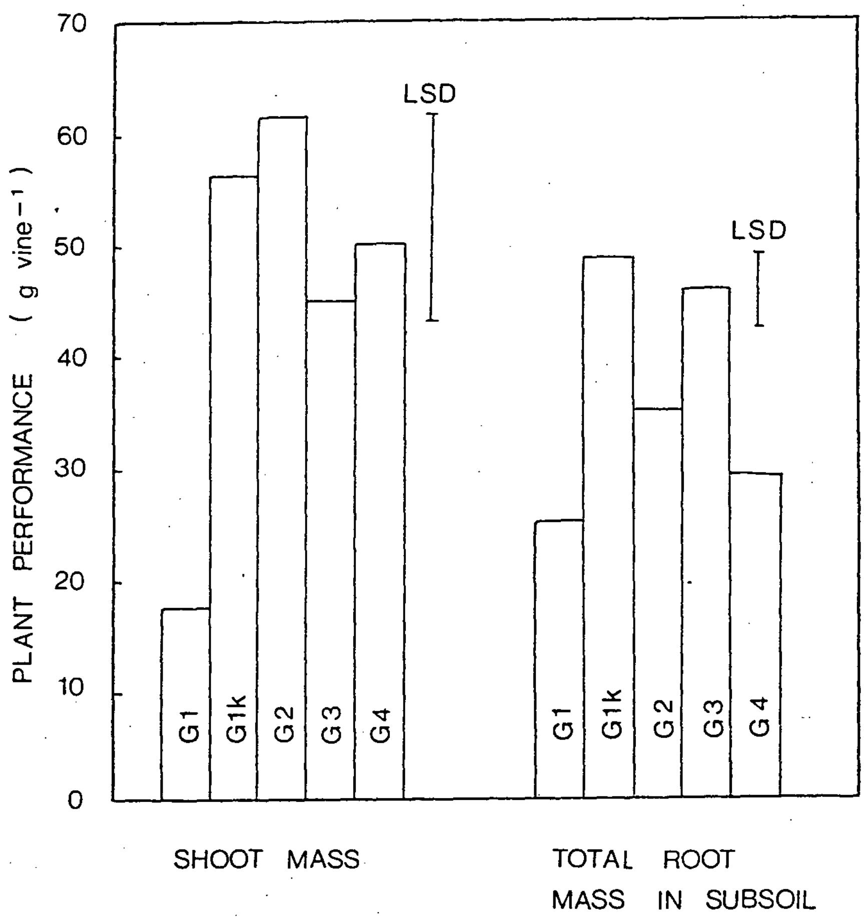


Fig. 2.4. Mean effect of soil type on grapevine shoot and root growth (G1 - Glenrosa sandy loam; G1k - Limed Glenrosa sandy loam; G1 - Calcareous Hutton sandy loam; G3 - Estcourt loamy sand; G4 - Hutton sandy loam).

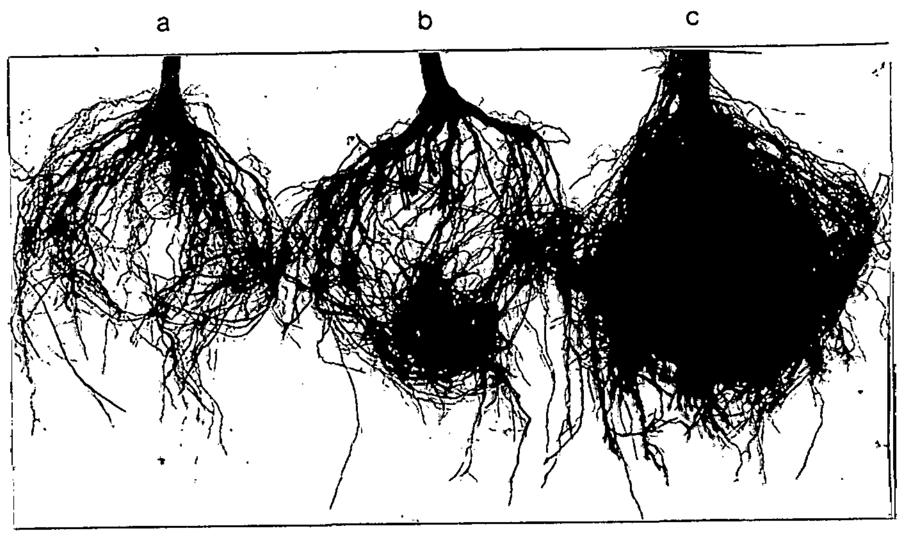


Fig. 2.5a. General root systems from the uncompacted topsoil of different soil types: (a) G4 - Hutton sandy loam; (b) G3 - Estcourt loamy sand; (c) G2 - Calcareous Hutton sandy loam.

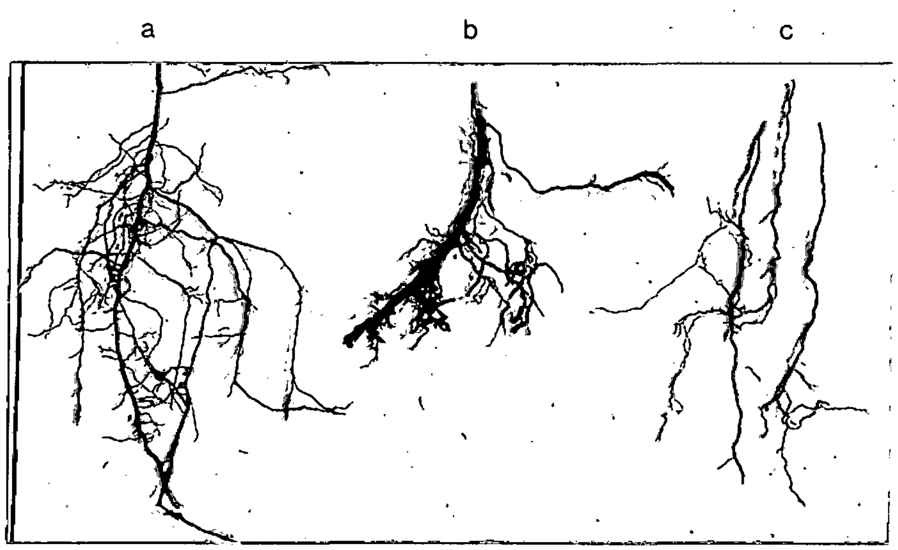


Fig. 2.5b. Individual roots from the uncompacted topsoil of different soil types: (a) G2 - Calcareous Hutton sandy loam; (b) G3 - Estcourt loamy sand; (c) G4 - Hutton sandy loam.

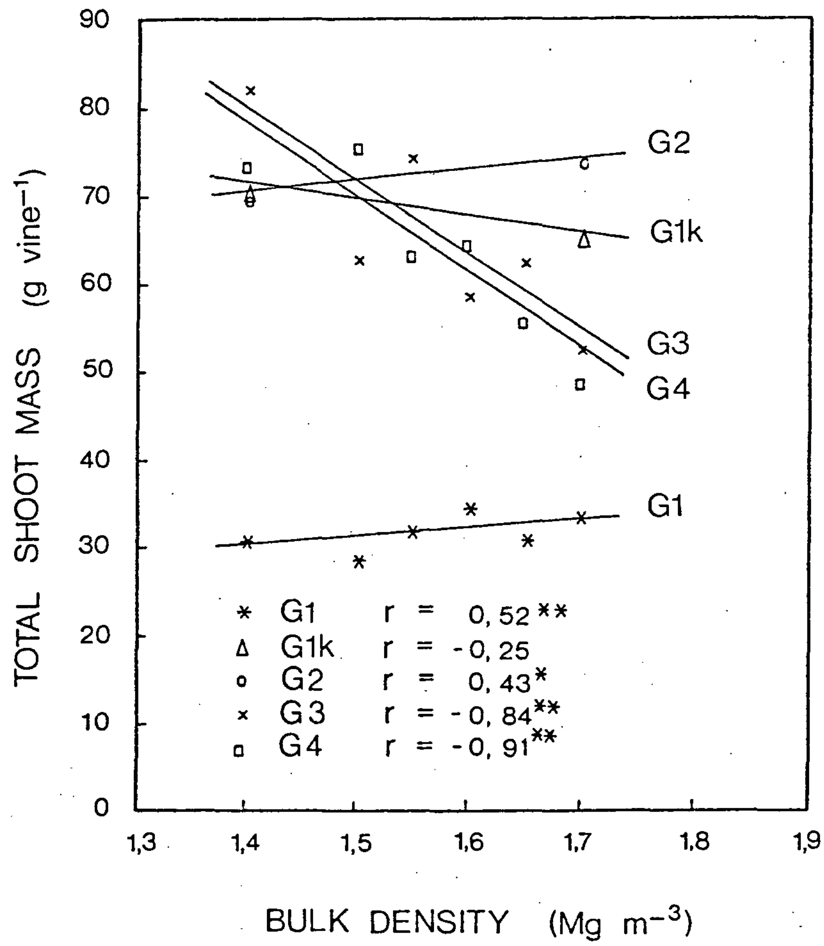


Fig. 2.6. Relationship between shoot mass and subsoil compaction of five soil types (G1 - Glenrosa sandy loam; G1k - Limed Glenrosa sandy loam; G2 - Calcareous Hutton sandy loam; G3 - Estcourt loamy sand; G4 - Hutton sandy loam).

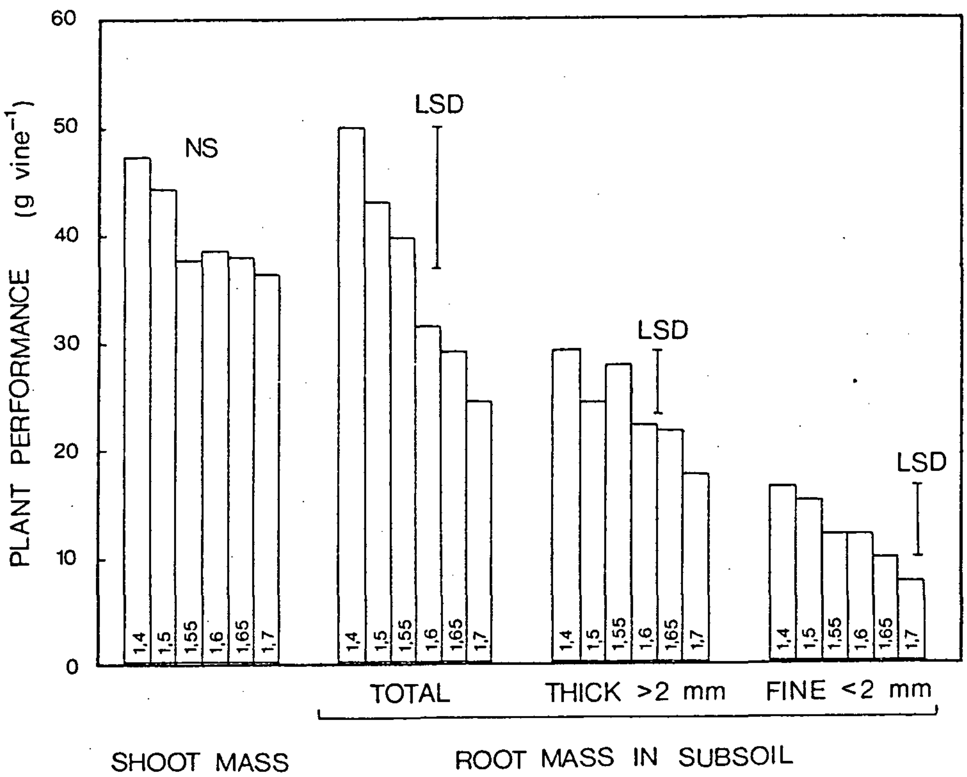


Fig. 2.7. Mean effect of subsoil compaction on grapevine shoot and root growth over all soil types (Figures within bars represent subsoil densities in Mg m$^{-3}$).

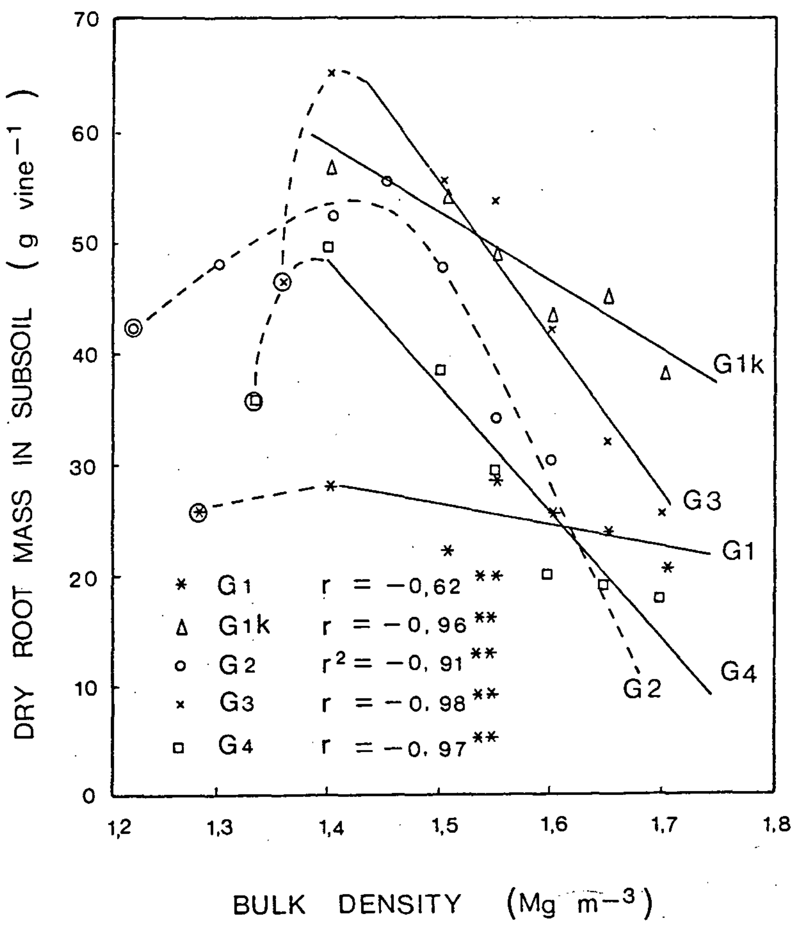


Fig. 2.8. Decrease in dry root mass in the subsoil as a function of increasing compaction for five soil types (G1 - Glenrosa sandy loam; G1k - Limed Glenrosa sandy loam; G2 - Calcareous Hutton sandy loam; G3 - Estcourt loamy sand; G4 - Hutton sandy loam).

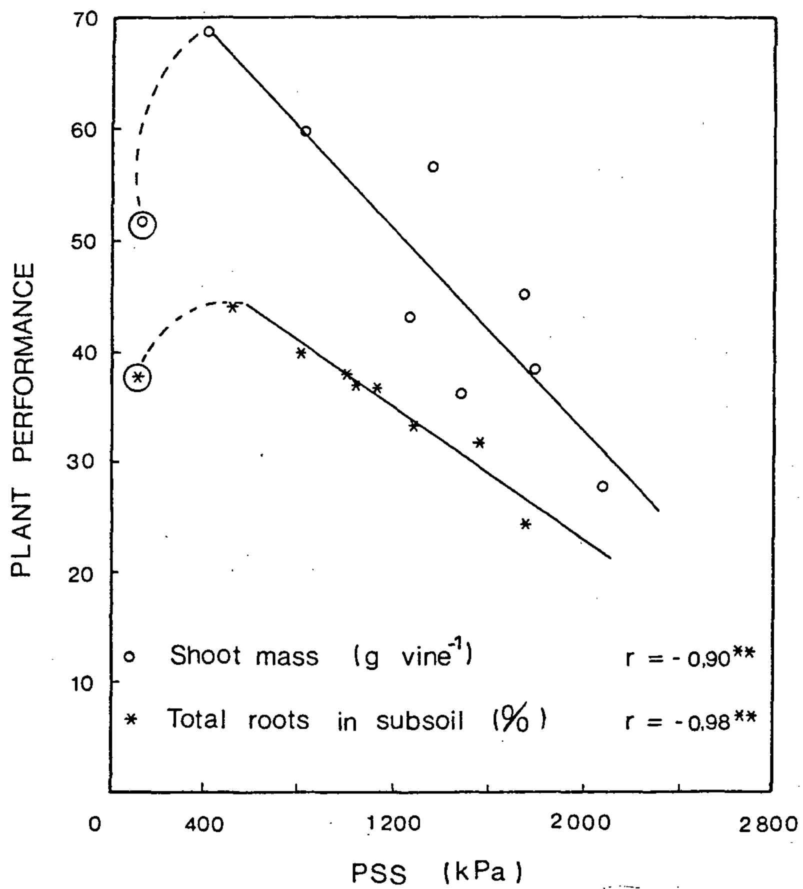


Fig.2.9. Relationship between penetrometer soil strength (PSS) and vine performance for G3 (Estcourt loamy sand).

# CHAPTER 3

## BULK DENSITY AND PENETRATION RESISTANCE AS INDICATORS OF THE POTENTIAL ROOTING VOLUME, AND THEIR RELATIONSHIPS WITH GRAPEVINE ROOT GROWTH IN A DEEP TILLAGE EXPERIMENT

## ABSTRACT

A major cause for the confinement beperking of grapevine roots to a specific volume of soil is naturally dense subsoils. The general practice is to alleviate such root growth limiting densities by deep tillage before the vineyards are being planted. It is however uncertain which soil physical properties describe such root impeding layers best. As a follow-up for a pot experiment, described in Chapter 2, three deep tillage techniques shallow ploughed; Ripped, Deep ploughed were evaluated in terms of the size and looseness of the available rooting volume. The effects of the different tillage methods on grapevine root growth were judged in terms of the cross-sectional area of soil disturbed (soil volume), bulk density (BD) and penetrometer soil strength (PSS). A residual loosening effect of deep tillage could still be measured 15 years after the treatments were applied. Most of the roots were confined beperk to the loose soil above the working depth of the implements. Linear relationships between BD and PSS, as well as between the maximum PSS per depth layer and the actual root number in that specific soil layer, were established. Available soil volume and aboveground grapevine performance did not correlate well, probably due to sporadic root penetration deeper into the intact subsoil and due to supplementary irrigations. Indications are that shallow soils recompact to higher densities than deeper soils.

## 3.1 INTRODUCTION

Grapevine roots must for many years grow in the same environment. To meet the requirements of longevity and efficiency of the roots, a good quality rooting environment is needed. Unfortunately, many soils in the Western Cape of the Republic of South Africa have naturally dense subsoils that physically impede grapevine root development. The current approach is to create a larger rooting volume through mechanical disruption of the dense subsoil by deep tillage. Saayman and Van Huyssteen (1980) and Saayman (1982) reviewed the literature regarding deep tillage or profile modification for vineyards. In addition, their deep tillage experiments showed the importance of adequate soil preparation under local conditions for improved grape yield. These authors were, however, unable to establish a definite relationship between physical parameters and root growth, although they established a positive linear relationship between rooting depth and aboveground grapevine performance. According to McCormack (1987), measurements of PSS and BD, and observations of root paths, have little value unless the impact of the observed condition on the yield of the crop can be determined. The relationship between aboveground vine growth and subsoil compaction was established in a pot experiment (Chapter 2), but it was unsure whether the results would be applicable to field conditions.

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The hypothesis for the present study was that different soil preparation techniques will yield rooting volumes differing in size and quality. Furthermore, this rooting volume might be described in terms of bulk density (BD) and penetrometer soil strength (PSS), which in turn can be related to grapevine root growth. As a consequence, this study set out to examine the persistence of deep tillage effects on a soil type with typical high natural BD's in the subsoil, and to relate BD and PSS to grapevine root growth under field conditions.

## 3.2 MATERIALS AND METHODS

The study was conducted at a soil preparation site reported earlier by Saayman (1982). Except for the soil type, location and grapevine cultivar, this trial was similar to the experiment of Saayman and Van Huyssteen (1980). A Colombar/143B Mgt vineyard was established at a plant spacing of 3,0 x 1,5 m on an acid Clovelly/Hutton sandy clay loam soil (Soil taxonomy classification: Xerochrept) at Stellenbosch. This is a highly weathered, well-drained yellow brown soil with a dense, structureless subsoil, which had high BD's in the natural state. Compared on a horizontal basis, the soil was texturally homogeneous (Saayman, 1982). The only chemical amelioration was a blanket application of superphosphate at a rate of 2 t $ha^{-1}$ at the time of ploughing.

For the purpose of this paper, the following three treatments are considered:

a) Shallow delve plough. One direction to a depth of *ca*. 300 mm.

b) Ripper. One direction to a depth of *ca*. 700 mm and at spacings of 800 mm.

c) Delve plough. One direction to a depth of *ca*. 700 mm.

Each treatment was replicated six times in a randomised block design for the original experiment. Only the four replicates of which the mean grapevine performance was nearest to the treatment mean of the six original replicates were selected for the purpose of this study. The four selected replicates were situated within 120 m radius. The vineyard received two supplementary irrigations of *ca*. 50 mm each during December and January of each year.

Field measurements of the soil physical properties for the present study were made during the summer (December), 15 years after the soil preparation treatments were applied. Selection of the measurement sites within each individual treatment plot was based on the mean grapevine performance as determined for the 21 experimental grapevines in each replication of the specific treatment. This was done in order to do the root studies at the most representative grapevine plant per plot, the latter being 36 m long.

Bulk densities were determined in triplicate per depth layer of 200 mm thickness, down to a depth of 800 mm, in open profile pits. The profile pits for sampling purposes and root studies were dug following the December irrigation. The rubber balloon method described by Blake (1965) for bulk density determination was used and holes of 1,1 $dm^3$ were excavated. Bulk densities were measured in the plant row position where no wheel compaction was possible after the vineyard was established. The average BD's measured on the experimental site before commencement of the trial were: 0 to 200 mm = 1,55 Mg $m^{-3}$; 200 to 400 mm = 1,61 Mg $m^{-3}$; 400 to 600 mm = 1,73 Mg $m^{-3}$; 600 to 800 mm = 1,75 Mg $m^{-3}$.

Grapevine roots were exposed on a vertical wall of the profile pits. A large frame, divided into 200 mm squares, was placed on the wall. This allowed plotting the locations of the roots to scale onto graph paper. The profile walls used for root studies were perpendicular to the rows, and midway between two adjacent vines in the row (Fig. 3.1). These data were used for the comparison of rooting depth and BD. The grapevine performance data, *i.e.* yield and shoot mass, reported by Saayman (1982) were used.

The penetrometer used to measure penetration resistance was similar to the one described by Carter (1967). It had a cone with a base area of 1,29 $cm^2$ and a $30^0$ cone tip. Prior to the PSS measurements, a second irrigation was applied after the December irrigation to the sites where the measurements were made. This was done to minimise the complicating effect of varying soil water contents, and to ensure a homogeneous wet profile with a matrix potential of approximately -25 kPa. Gravimetric water contents at the time of PSS measurements confirmed that this precautionary measure was successful. The penetrometer studies were conducted adjacent to the open profile pits alongside the walls against which the roots were studied and where the bulk density samples were taken.

Penetrometer soil strengths (PSS) were measured to a depth of 900 mm and at horizontal intervals of 250 mm across the interrow space (3 m wide) for all four replicates of a particular treatment (Fig. 3.1). These transects were perpendicular to the rows, the tractor tracks and the primary tillage direction. At each measurement site, *i.e.* on each of the four replicates of a treatment, three transects were measured only 150 mm apart to minimise the effect of spatial variability (Burgess and Webster, 1980; Moolman and Van Huyssteen, 1989). It is possible that measurements made over such a small area might not provide a true estimate of the plot mean. However, for the purpose of this study, it was considered to be of greater importance to have an accurate description of PSS at carefully selected measurement sites, and where the root studies were done, rather than to have a plot mean value obtained with the same number of observations, but spread over a larger area.

Although a continuous measurement of PSS over depth was provided, data were read at 50 mm intervals. The PSS values were then averaged according to either depth or horizontal position, based on the particular visual representation or the resulting statistical analyses. It was thus possible to get a cross-sectional view of an area of 900 mm deep and 3 000 mm wide per measuring site with data points at 50 mm depth- and 250 mm horizontal intervals. From the individual plots of PSS *versus* soil depth for each horizontal position on the transect, the depth could be identified where a predetermined threshold soil strength was first encountered, and which extended over a depth increment of 100 mm. These values were averaged and plotted as iso-strength lines.

The data were compared between treatments and depths using analysis of variance (Snedecor and Cochran, 1980). Mean values were first computed by transect position, and these individual position means on the transect were averaged over the four replicates to give overall treatment means. In addition, means for on and off the wheel tracks for each of the three treatments were determined.

## 3.3 RESULTS AND DISCUSSION

The BD data are summarised in Table 3.1. The loosening effect after 15 years was still measurable in the 400 to 600 mm depth layer of the deep ploughed treatment. This depth layer had a highly significant lower BD than the corresponding depth layer of the other three treatments. Compared on the basis of treatment means, the deep ploughed treatment had a significantly lower BD than all the other treatments. In the ripper furrows, the mean BD did not differ significantly from that between the ripper furrows. No statistically significant difference between depths was measured for the shallow ploughed treatment, while the only significant difference for the deep ploughed treatment was between the 400 to 600 mm and the 600 to 800 mm depth layers. In the case of the ripper treatment, both of the upper measuring depths in the topsoil had significantly lower BD's than the two subsoil layers deeper than

400 mm for both positions.

The physical disruption of the soil profile by deep tillage decreased BD to varying degrees. The high BD in the subsoil of the shallow ploughed and ripper treatments illustrated the natural high density of this soil. The ripper and shallow plough treatments were equally ineffective to lower the BD of this soil type. Although not statistically significant, the BD's of the 0 to 400 mm depth layer of the deep ploughed plot and on the ripper furrow position was lower than that of the between furrows position and the shallow ploughed plots. This fact, together with the low BD in the 400 to 600 mm depth layer of the deep ploughed treatment showed that this soil was stable against spontaneous recompaction provided it had been effectively loosened. In contrast, the average BD on the wheel tracks was 1,71 Mg $m^{-3}$ in the 0 to 200 mm depth layer (data not included in Table 3.1), which illustrated the sensitivity of this soil to wheel compaction after it had been loosened. Similar results were reported by Van Huyssteen (1983).

The degree of recompaction which occurred in the 0 to 200 mm and 200 to 400 mm depth layers of the shallow ploughed plots and between ripper furrows positions tended to be higher than that of the other two treatments. The reason for this is not clear, but it might be an indication that recompaction of a loose soil layer overlying a dense soil layer at a relatively shallow depth might be more serious due to the concentration of compaction forces within a smaller volume of soil. The average BD in the 0 to 200 mm depth layer directy after application of the treatments 15 years ago was 1,403 Mg $m^{-3}$.

The treatment mean soil strengths *versus* depth are illustrated in Figure 3.2 and the mean soil strengths per depth layer are given in Table 3.2. In brief, these results confirmed that of BD in Table 3.1. Even on the deep ploughed plots high soil strengths, exceeding 3 000 kPa, were measured in the subsoil.

The mean soil strength at different positions are presented in Table 3.3. Only in the case of the top 150 mm of the deep ploughed treatment (Table 3.3c) did wheel compaction increase PSS in a statistically significant way compared to that of the other positions. Nevertheless, it was clear that wheel compaction increased PSS in at least the topsoil of this experiment. Similar to BD (Table 3.1), the results of Tables 3.3a-c showed a tendency for higher soil strengths to occur in the topsoil overlying a dense subsoil at a relatively shallow depth.

The iso-strength lines of selected replicates of the three treatments are presented in Figure 3.3. The contour lines for the average over all the replicates are not presented as it did not give a realistic picture of implement action on PSS. Averaging of the replicates, had an unnatural smoothing effect on the contour lines. This is due to the fact that the penetrometer readings that were taken at equal distances from a reference point, the root stock, on different replicates of a teatment, did not always coincide with the same position, *e.g.* wheel track or tool path. However, similar visual arrangements were made for each replicate which were then used to determine the average volume of loosened soil per treatment.

The degree of loosening was defined as the cross-sectional area ($m^2$) in each profile where the observed PSS readings were less than an arbitrarily chosen threshold cone resistance value. Available soil volume ($m^3$) per grapevine was calculated as the loosened cross-sectional area times 1,5 m, the planting distance in the row. Threshold cone resistance was selected by plotting the average loosened soil volume against various PSS threshold values (Fig. 3.4). Soil volume increased almost linearly with increasing threshold PSS on the shallow plough and ripper treatments, but a sharp increase (1,21 $m^3$) in soil volume was noted for a threshold PSS of 2 000 to 3 000 kPa in the case of the deep ploughed treatments. Above a threshold PSS of 3 000 kPa the slopes of all three curves were very similar. Thus a PSS of 3 000 kPa was selected as threshold PSS value for future calculations. The 3 000 kPa PSS value coincided with the 117, 250 and 600 mm depths, respectively, for the shallow ploughed, ripped and deep ploughed treatments (Fig. 3.2), which is illustrative of the differences in effective rooting depth per treatment as determined by PSS.

The relationship between PSS and root number per depth for this soil type is illustrated in Figure 3.5. The fitted line indicates zero root growth at a PSS of 8 000 kPa on this sandy clay loam soil. Like the pot experiment (Chapter 2), a linear decrease in actual root number with increasing PSS was found. This explained the different total root numbers per treatment, *viz.*

| Treatment | Mean PSS per treatment | Mean total root number |
|---|---|---|
| Shallow plough | 5 460 kPa | 270 roots |
| Ripper | 4 840 kPa | 351 roots |
| Deep plough | 3 690 kPa | 526 roots |

A linear relationship between BD and PSS was found in the pot experiment (Chapter 2). A similar relationship between BD and PSS, in this case the maximum PSS per depth layer, is also illustrated in Figure 3.6. The threshold PSS value of 8 000 kPa at which no root growth is projected to occur on this sandy clay loam soil (Fig. 3.5) coincides with a BD of 1,82 Mg $m^{-3}$ in Figure 3.6. Vepraskas (1988) estimated that root penetration of tobacco plants would be zero at BD's of 1,85; 1,82; 1,81 and 1,80 Mg $m^{-3}$ on sand, loamy sand, sandy loam and sandy clay loam soils, respectively. However, the latter author found that the roots of tobacco plants were already impeded at lower BD's (compare page 2.2 of this thesis). This should be further investigated in future field studies.

There is a significant correlation between the aboveground grapevine performance and available soil volume (Table 3.4). The low correlation coefficients are probably due to the supplementary irrigation which moderated the potential for water stress to occur in the soils with the smaller available rooting volume. This is in accordance with results of Andersen and Odneal (1984) who found that irrigation can mask the negative effect (poor shoot growth) of small rooting volumes on grapevine performance, at least in young vineyards. Saayman (1982) reported that although most of the roots were found above the working depth, some grapevine roots penetrated beyond the depth of loosening and that water uptake through these sporadic deep roots, despite their limited numbers, might mask the effect of the small available rooting volume. The root numbers in the unloosened subsoil layers were as follows:

| Treatment | Depth | Actual root numbers |
|---|---|---|
| Shallow ploughed | 500 to 750 mm | 43 $m^{-2}$ (11,9% of total) |
| | 750 to 1000 mm | 23 $m^{-2}$ ( 6,2% of total) |
| Ripped | 750 to 1000 mm | 47 $m^{-2}$ ( 9,7% of total) |
| Deep ploughed | 750 to 1000 mm | 52 $m^{-2}$ ( 7,4% of total) |

## 3.4 SUMMARY AND CONCLUSIONS

The results indicated that, on this soil type, after 15 years the beneficial effect of deep tillage was still measureable as exhibited by low BD's and PSS values. The topsoils of all the different treatments were effectively loosened at the onset of the experiment. However, after 15 years the topsoils overlying the shallower working depths had higher BD's than those of soils where the naturally dense layers occur at greater depths, the latter being the result of a greater working depth. Mean PSS correlated well with root concentration ($R^2$ = 96,4%$^{**}$) and supported the results obtained in the pot experiment (Chapter 2).

Similar to the pot experiment, and in accordance with literature, occasional deep root penetration into the intact subsoil occurred. This specific soil fractured along zones of weakness, presumably formed by intensive drying of the soil by the roots concentrating on the working depth and/or by relaxation of the dense soil immediately underneath the working depth.

In this study the cross-sectional view of transects of PSS measurements along transects perpendicular to the direction of tillage and traffic supported the observation in the literature (Cassel, 1982; O'Sullivan *et al.*, 1987) that the variability in cone resistance may be associated with tillage and traffic. Therefore, in compaction studies, great care should be taken to define the position of PSS and bulk density measurements, a recommendation also made by Cassel (1982).

* tabel 3.1 en tabel op bl.

Iso-strength lines supplied a visual impression of the homogeneity of the rooting volume. Deep ploughing increased both the vertical and horizontal homogeneity of the soil profile more than ripping or shallow ploughing did. The number of grapevine roots was primarily determined by the size and quality of the rooting medium. Consequently, soil preparation techniques should strive to create a large and homogeneous rooting volume in order to get a well-distributed rooting system.

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Bulk density and PSS remain effective parameters to describe the compaction status in the field. The main value of the results of this study was to provide realistic information about these two parameters as indicators of the quality of the rooting volume in terms of looseness. The information gained with this experiment, together with those of Chapter 2, will have practical application in viticulture, *e.g.* to explain poor grapevine performance due to root impeding layers occurring somewhere in the soil profile. However, the soil information pertinent to compactibility is not extensive enough to make specific deep tillage recommendations to farmers because

1) knowledge of the occurrence and nature of soil compaction on other soil types, and in the different viticultural areas, are lacking;

2) we are uncertain on research tools needed to extrapolate this data to other soil types; and

3) we need additional information on BD and PSS in relation to other soil properties.

In the following chapters, aspects pertaining to points 1) to 3) above will receive attention. Further studies of the soil volume/plant available soil water interaction are needed to supply a more definite understanding of the required rooting volume for grapevines.

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Table 3.1. Bulk densities measured 15 years after different soil preparation treatments were applied on a Clovelly/Hutton soil (Soil taxonomy classification: Xerochrept) at Stellenbosch.

| Depth (mm) | Bulk densities (Mg m$^{-3}$) Shallow plough | Ripper Between furrows | Ripper On furrows | Deep plough | Depth mean[1] | D-value (0,05) for treatments per depth |
|---|---|---|---|---|---|---|
| 0-200 | 1,62 | 1,62 | 1,58 | 1,59 | 1,60 | NS[2] |
| 200-400 | 1,64 | 1,63 | 1,53 | 1,57 | 1,59 | NS |
| 400-600 | 1,73 | 1,75 | 1,71 | 1,48 | 1,67 | 0,12 |
| 600-800 | 1,73 | 1,76 | 1,76 | 1,69 | 1,73 | NS |
| Treatment mean | 1,68 | 1,69 | 1,64 | 1,58 | 1,65 | - |
| D-value (0,05) for depths per treatment | NS | 0,08 | 0,10 | 0,16 | - | 0,06 |

[1] Mean of all treatments. For the purpose of comparison, the two positions of the ripper treatment were considered as separate treatments.

[2] NS = Not significant at 5% level.

Coefficient of variation = 4,41%.

Significance [D-value(0,05)] for: Depth x Treatment = 0,165.
Depth mean = 0,061.
Treatment mean = 0,061.

Table 3.2. Mean soil strength per depth layer 15 years after different soil preparation treatments were applied on a Clovelly/Hutton soil (Soil taxonomy classification: Xerochrept) at Stellenbosch.

| Depth (mm) | Mean soil strength (kPa x $10^{-2}$) Shallow plough | Ripper | Deep plough | Depth mean | D-value (0,05) for treatments per depth |
|---|---|---|---|---|---|
| 0-250 | 31,02 | 23,99 | 20,47 | 25,16 | NS[1)] |
| 250-500 | 48,62 | 39,54 | 24,36 | 37,51 | 9,98 |
| 500-750 | 68,64 | 61,67 | 32,17 | 54,16 | 11,95 |
| 750-1000 | 70,00 | 68,48 | 64,99 | 67,82 | NS |
| Treatment mean | 54,57 | 48,42 | 35,50 | 46,16 | - |
| D-value(0,05) for depths per treatment | 8,31 | 8,57 | 6,74 | - | 4,15 |

1)NS = Not significant at 5% level.

Coefficient of variation 12,67%.

Significance [D-value(0,05)] for: Depth x Treatment = 11,14.
Treatment mean = 4,15.
Depth mean = 4,15.

Table 3.3a. Mean soil strength per depth layer at different positions in the shallow ploughed soil preparation treatment of a Clovelly/Hutton soil (Soil taxonomy classification: Xerochrept) at Stellenbosch.

| Soil depth (mm) | Mean soil strength (kPa x $10^{-2}$) | | | |
|---|---|---|---|---|
| | On vine rows | Middle between rows | On wheel tracks | D-value(0,05) |
| 50 | 14,0 | 14,2 | 25,1 | NS |
| 100 | 20,5 | 21,3 | 35,3 | NS |
| 150 | 28,7 | 29,1 | 39,2 | NS |
| 200 | 31,2 | 36,0 | 43,6 | NS |
| 250 | 34,6 | 42,5 | 48,5 | NS |
| 300 | 41,8 | 46,6 | 53,2 | NS |
| 400 | 53,7 | 54,3 | 59,9 | NS |
| 500 | 60,6 | 64,4 | 67,4 | NS |
| 600 | 70,0 | 70,0 | 70,0 | NS |
| Mean | 39,46 | 42,05 | 49,13 | 4,1 |

Significance [D-value(0,05)] for: Depth x Position = 18,55.
Depth mean = 4,10.
Position mean = 4,10.

Coefficient of variation = 20,8%.

(continued on next page)

Table 3.3b. Mean soil strength per depth layer at different positions in the ripped soil preparation treatment of a Clovelly/Hutton soil (Soil taxonomy classification: Xerochrept) at Stellenbosch.

| | Mean soil strength (kPa x $10^{-2}$) | | | |
|---|---|---|---|---|
| Soil Depth (mm) | On vine rows | Middle between rows | On wheel tracks | D-value(0,05) |
| 50 | 14,3 | 16,5 | 22,1 | NS |
| 100 | 19,2 | 18,7 | 26,3 | NS |
| 150 | 24,3 | 23,9 | 28,0 | NS |
| 200 | 26,1 | 26,1 | 30,5 | NS |
| 250 | 27,2 | 30,0 | 30,8 | NS |
| 300 | 34,4 | 36,7 | 36,3 | NS |
| 400 | 44,5 | 46,9 | 45,0 | NS |
| 500 | 56,2 | 53,8 | 52,9 | NS |
| 600 | 66,6 | 63,6 | 65,2 | NS |
| Mean | 34,76 | 35,13 | 37,46 | NS |

Significance [D-value(0,05)] for: Depth x Position = 17,91.
Depth mean = 6,20.
Position mean = 6,20.

Coefficient of variation = 24,5%

(continued on next page)

Table 3.3c. Mean soil strength per depth layer at different positions in the deep ploughed soil preparation treatment of a Clovelly/Hutton soil (Soil taxonomy classification: Xerochrept) at Stellenbosch.

| | Mean soil strength (kPa x $10^{-2}$) | | | |
|---|---|---|---|---|
| Soil Depth (mm) | On vine rows | Middle between rows | On wheel tracks | D-value(0,05) |
| 50 | 10,2 | 7,2 | 21,7 | * |
| 100 | 16,0 | 13,2 | 25,2 | * |
| 150 | 20,1 | 15,5 | 27,6 | * |
| 200 | 20,9 | 19,5 | 29,5 | NS |
| 250 | 21,3 | 21,6 | 29,1 | NS |
| 300 | 21,5 | 22,7 | 25,1 | NS |
| 400 | 22,7 | 25,9 | 22,9 | NS |
| 500 | 25,1 | 28,5 | 26,2 | NS |
| 600 | 36,6 | 33,2 | 34,3 | NS |
| Mean | 21,6 | 20,81 | 26,84 | 5,1 |

Significance [D-value(0,05)] for: Depth x Position = 11,47.
Depth mean = 5,10.
Position mean = 5,10.

Coefficient of variation = 24,3%.

Table 3.4. Relationship between soil volume at two selected threshold penetrometer soil strengths and vine performance on a Clovelly/Hutton soil (Soil taxonomy classification: Xerochrept) at Stellenbosch.

| Treatment | Soil volume ($m^3$) at different threshold strengths (kPa) | | Vine performance[1] | |
|---|---|---|---|---|
| | 0-3 000 (kPa) | 0-5 000 (kPa) | Yield (kg vine$^{-1}$) | Shoots (kg vine$^{-1}$) |
| Shallow ploughed | 0,67 | 1,40 | 36,84 | 4,41 |
| Ripped | 1,21 | 2,14 | 43,42 | 5,83 |
| Deep ploughed | 2,25 | 3,14 | 42,87 | 6,20 |

For 0 to 5 000 kPa: Yield = (4,8 x Soil volume) + 33,96 [$r = 0,34^{*}$].
Shoots = (1,2 x Soil volume) + 3,71 [$r = 0,61^{**}$].

[1] Total over last 4 seasons.

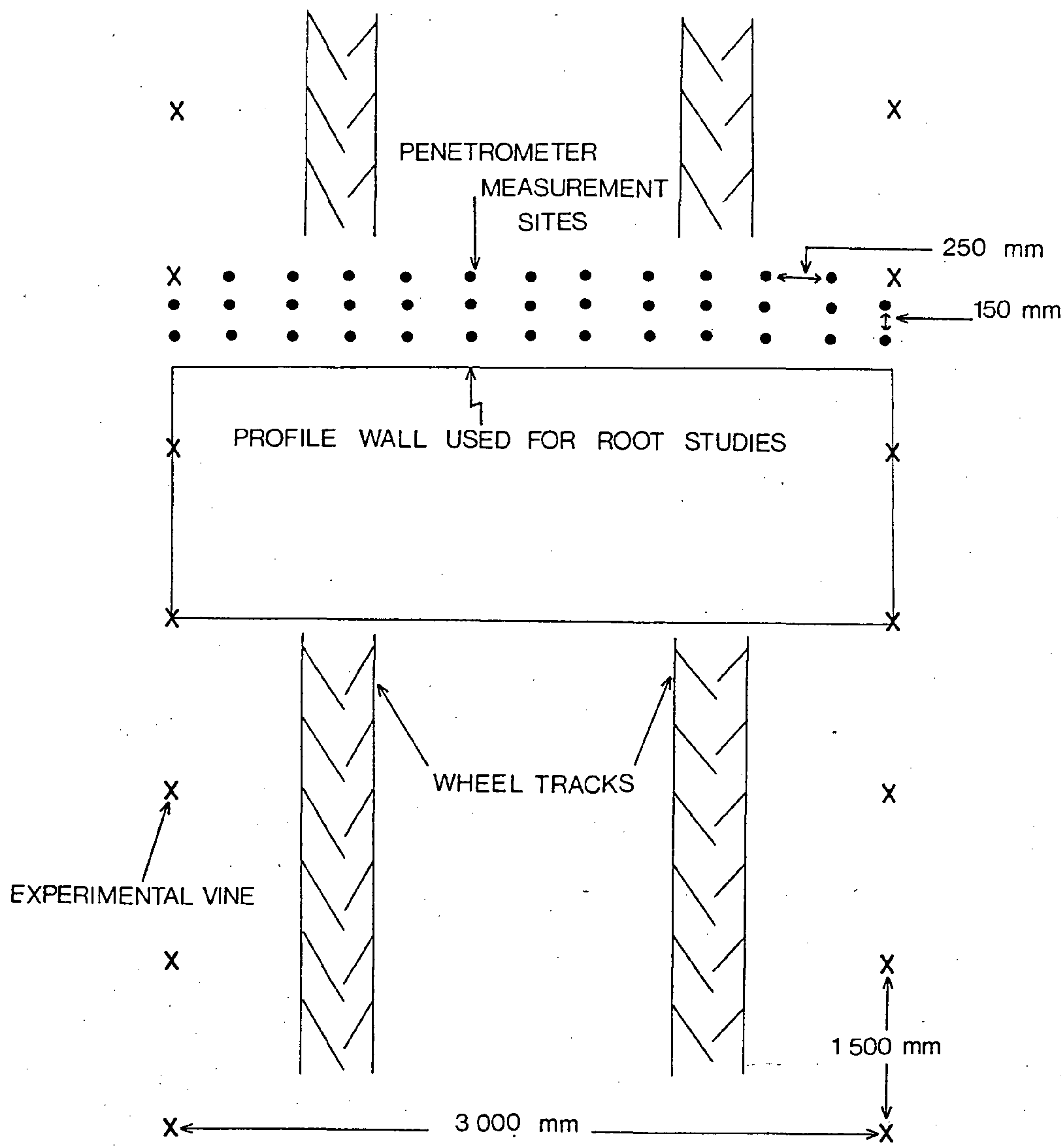


Fig. 3.1. Schematic presentation (not to scale) of penetrometer measurement sites on one replication in the experimental vineyard. Four such replications were measured per soil preparation treatment.

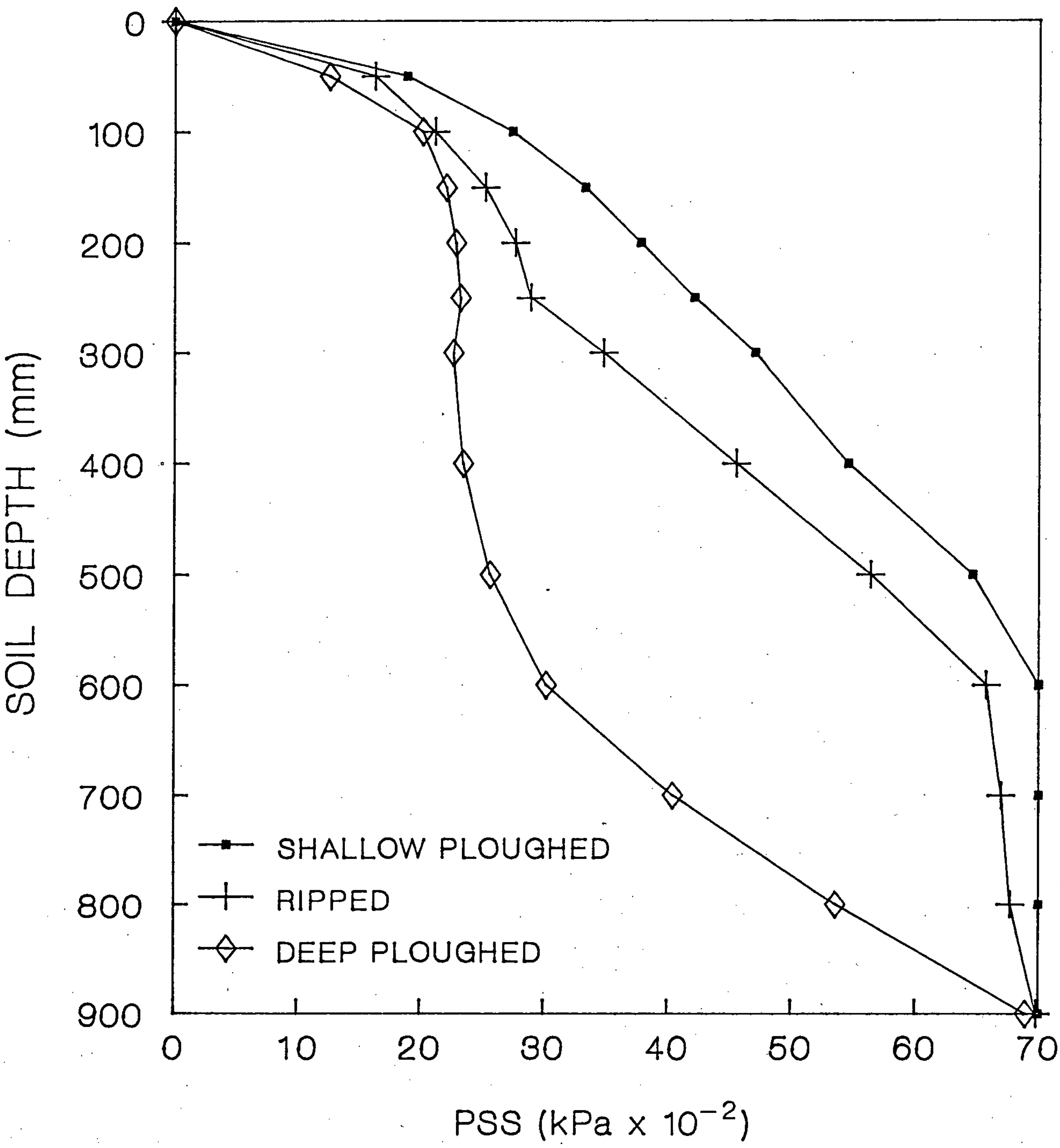


Fig. 3.2. Differences in mean soil strength (PSS) with depth, measured 15 years after different soil preparation methods were applied on a Clovelly/Hutton soil (Soil taxonomy classification: Xerochrept) at Stellenbosch. Data are shown regardless of position effects, *i.e.* data over transect positions across the rows were averaged. (Each point represents 156 values.)

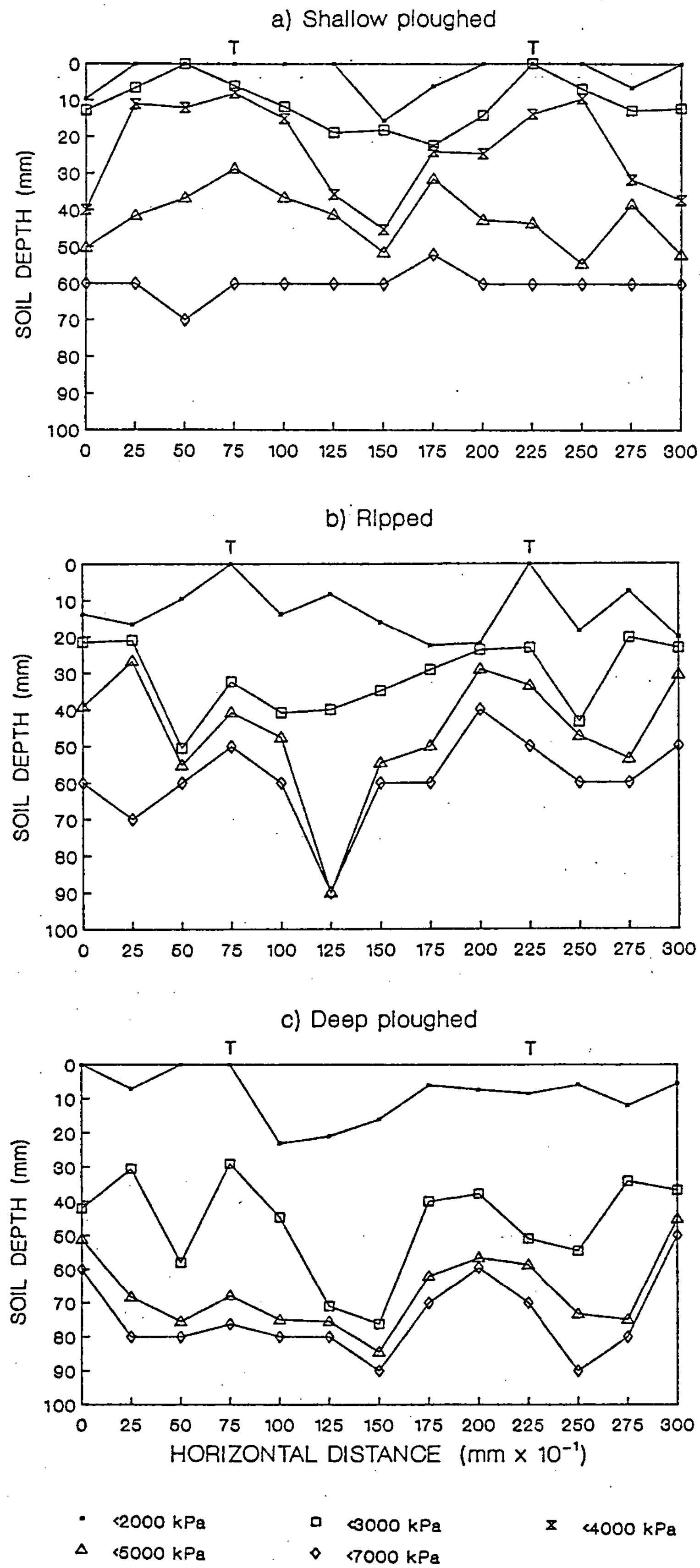


Fig. 3.3. Iso-strength lines to illustrate the variation in penetrometer soil strength in depth across the sampling transects representative of the three different soil preparation techniques on a Clovelly/Hutton soil (Soil taxonomy classification: Xerochrept) at Stellenbosch. The letter T above the figures indicates wheel track position.

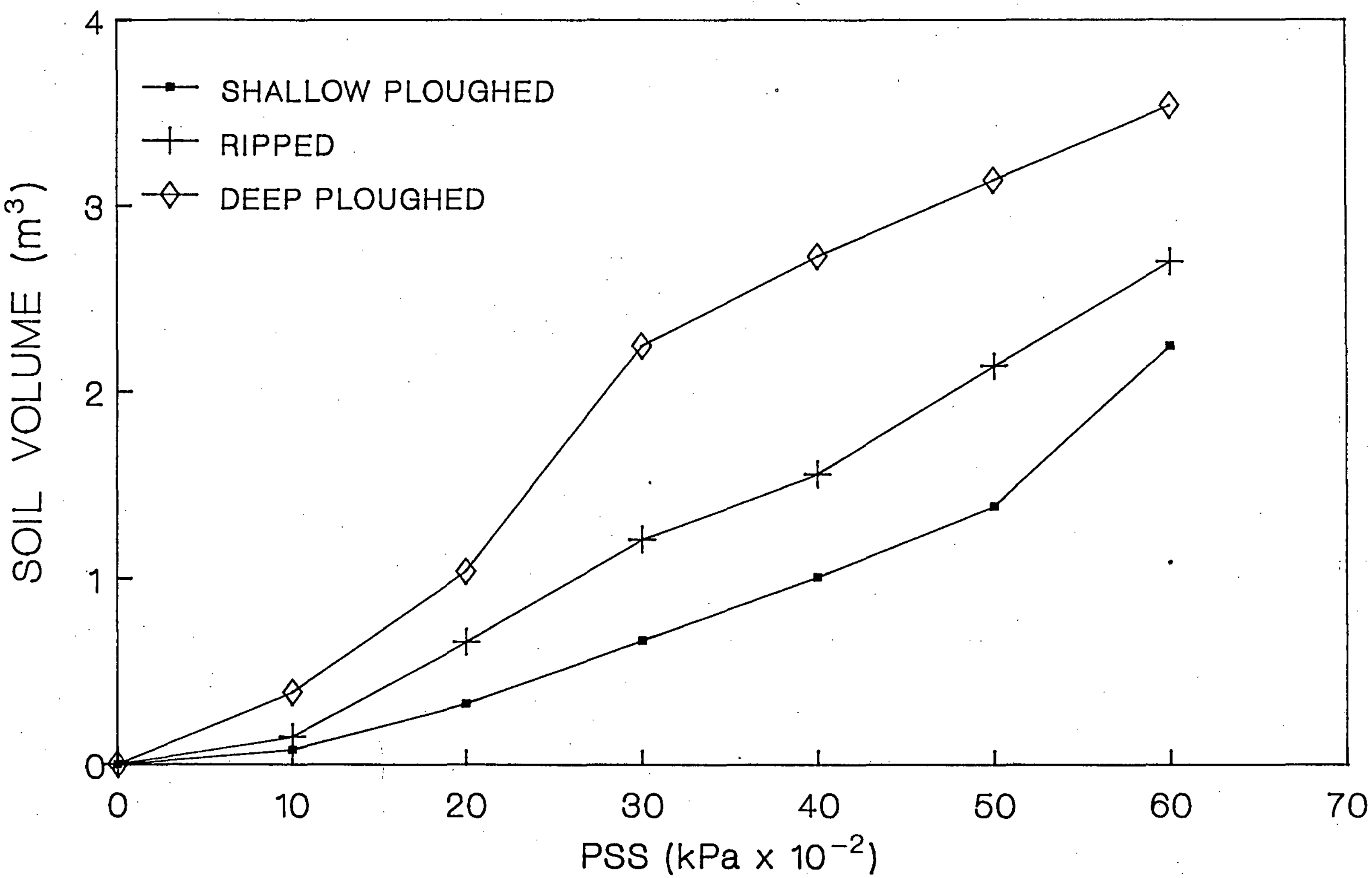


Fig. 3.4. Relationship between soil volume and threshold penetrometer soil strengths (PSS) for three soil preparation methods on a Clovelly/Hutton soil (Soil taxonomy classification: Xerochrept) at Stellenbosch. (Each data point represents a mean of 18 values.)

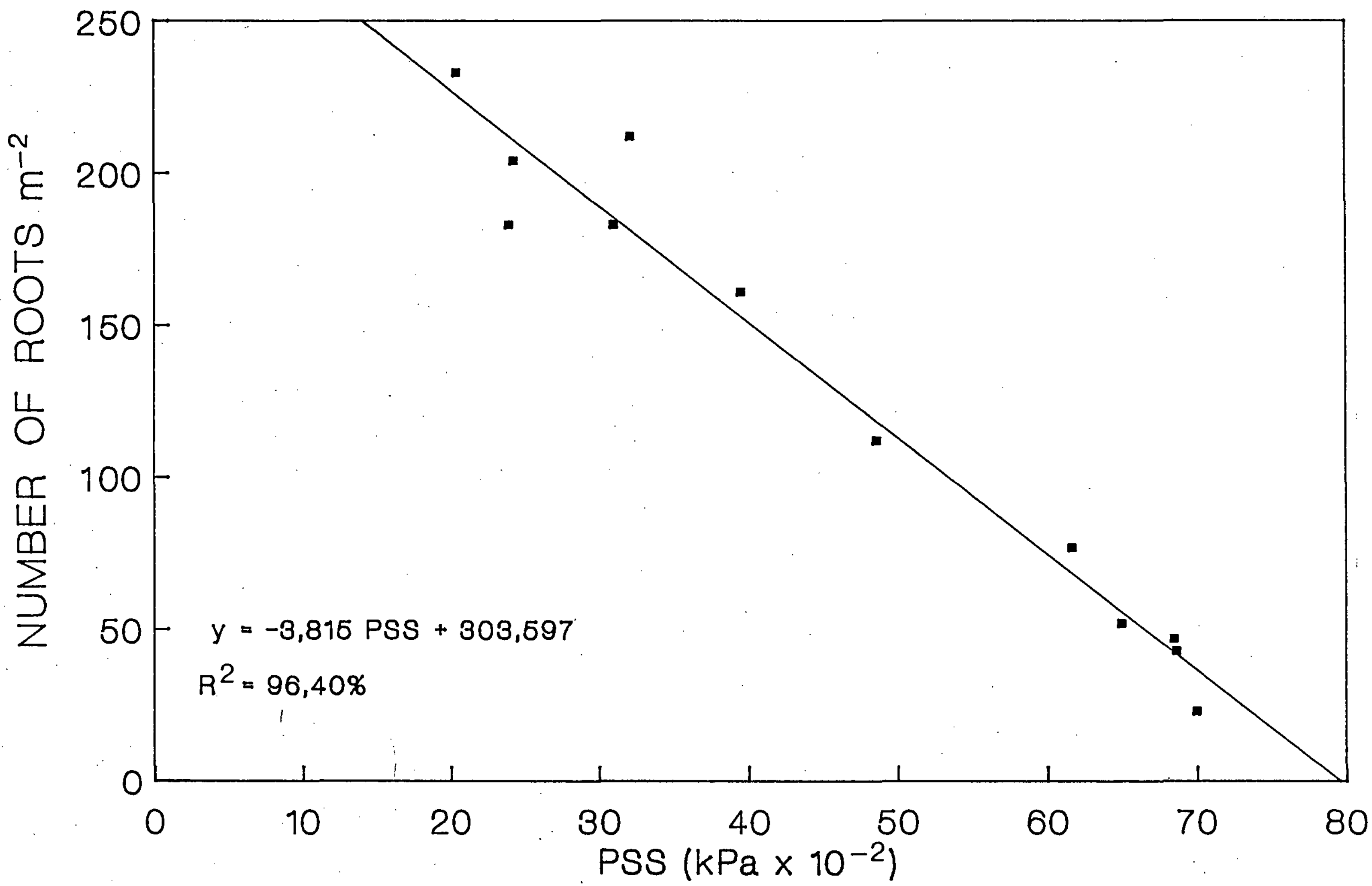


Fig. 3.5. Relationship between the actual root numbers m$^{-2}$ and the mean penetrometer soil strength (PSS) per depth layer of 250 mm thickness as determined in a soil preparation trial on a Clovelly/Hutton soil (Soil taxonomy classification: Xerochrept) at Stellenbosch.

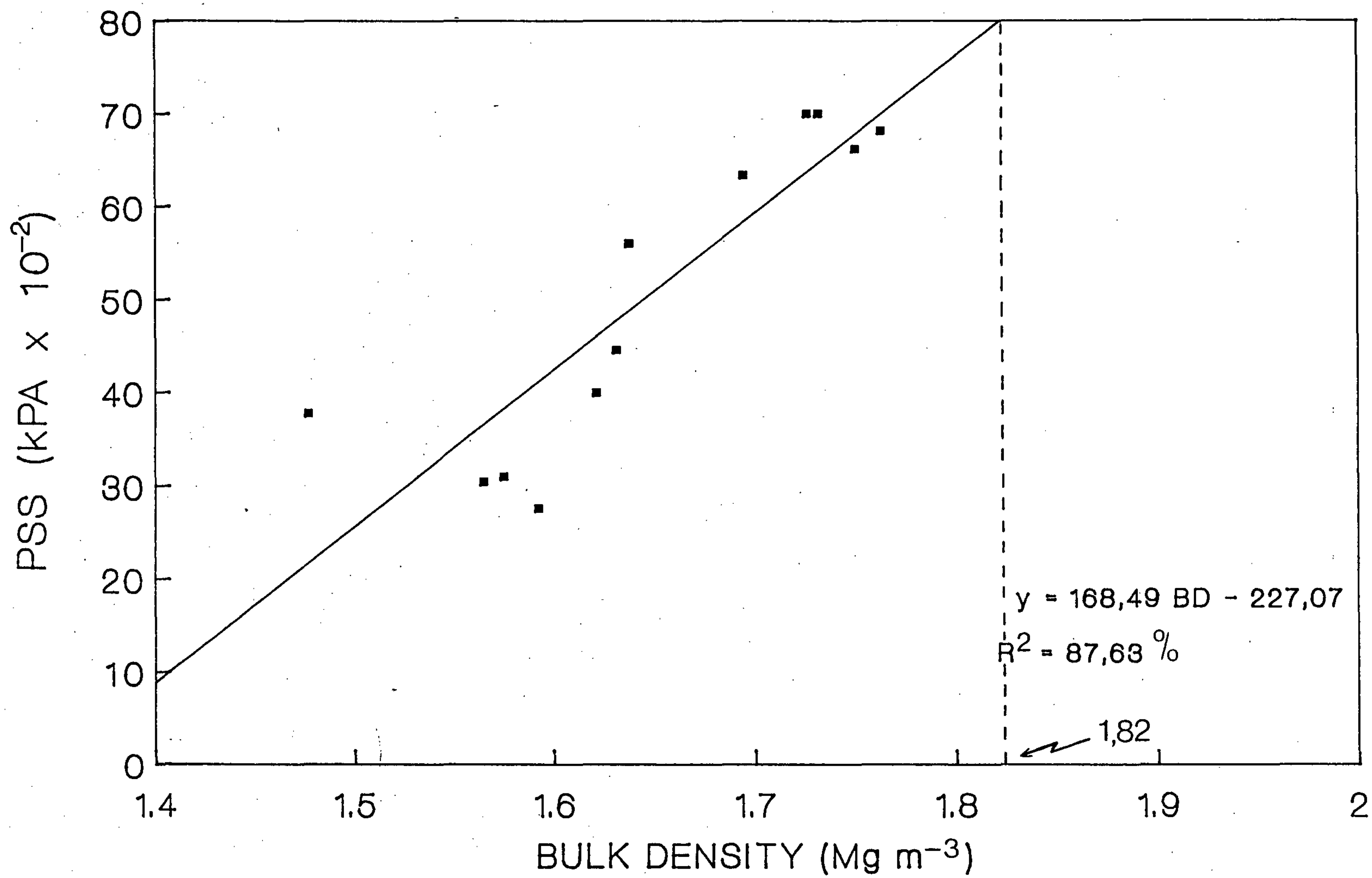


Fig. 3.6. Relationship between bulk density and penetrometer soil strength (PSS) as determined in a deep tillage experiment on a Clovelly/Hutton soil (Soil taxonomy classification: Xerochrept) at Stellenbosch.

# CHAPTER 4

# INVESTIGATION OF THE COMPACTION PROBLEMS IN VINEYARD SOILS

## ABSTRACT

Grapevine root growth is impeded by compaction. The severity of compaction in the field varies with soil types. A opname survey approach was used to collect a population of soil samples and then describe compaction, both qualitatively and quantitatively, at each sampling site. A total of 71 soil samples, collected from 50 profiles, comprising of a wide textural range was collected in the most important viticultural areas of the Republic of South Africa (RSA). A complete textural separation and properties such as modulus of rupture (MOR), maximum compactibility (MBD), aggregate stability (AS) as well as various chemical analyses were done on the soils. Uneven growth due to poor root penetration was one of the first symptoms of compaction in the field. Rooting patterns were direct indicators of compaction. Penetrometer soil strength (PSS) measurements were found to be relatively easy and an effective tool in identifying the zones of soil compaction in the field. This survey supplied background information in understanding the compaction problem of the vineyards in the RSA and served as introductory work to a laboratory study on the assessment of soil compactibility.

## 4.1 INTRODUCTION

Agriculturalists and farmers are slow to acknowledge the nadelige detrimental effects of soil compaction in vineyards. This is because the compaction effects do not appear as a single symptom on aboveground growth, and furthermore these effects are onbekend obscured until other soil management practices are optimal. Additionally, the roots which might give an indication of subsoil conditions are usually the least considered topic in field investigations and experiments, thus, the compaction effects through the root system on grapevine performance are normally overlooked. (In Saam met conjunction with) the conclusion of Taylor (1974), our voorlopige preliminary investigations in the field showed that grape yield losses ascribed to soil compaction resulted from factors associated with restricted root systems, such as increased plant water stress and/or nutrient stress, rather than from a direct effect of excessive soil strength. Therefore, the rooting depth attained on any soil determines its land use capability and how the soil should be managed.

Research in several local soil management trials has elucidated the relationships between soil management practices, bulk density, soil strength and root growth of grapevines under South African conditions (Saayman and Van Huyssteen, 1980; Van Huyssteen and Weber, 1980; Van Huyssteen, 1983), but never succeeded in providing guidelines for extrapolation of this data to soil types other than those investigated. In Chapter 2 of this dissertation, the results of the pot experiment showed that differences in rooting characteristics varied with soil compaction depending upon the soil type. The effect of available rooting volume, as determined by selected PSS boundaries, on grapevine performance was shown in a field experiment in Chapter 3 of this dissertation. Due to the high variability in soil types in the important viticultural areas of the RSA, it becomes difficult, if not impossible, to extrapolate current understanding of soil compaction problems to other field situations.

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This chapter deals with the broader perspective of the nature and scope of soil compaction problems in vineyards. The purpose is to provide a structure for orientating this whole study and to clarify the "what", "how" and "why" of a systematic approach towards assessing and managing soil compactibility.

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The hypothesis underlying this field scale survey is as follows: Depending on soil type, even subtle increases in compaction can cause impeded grapevine root penetration in the field. Additionally, the grapevine root does not discriminate between man-made compaction and that as a result of natural soil forming processes.

## 4.2 MATERIALS AND METHODS

### 4.2.1 Selection, sampling and preparation of soils

The following assumptions and criteria were used in the selection and preparation of soils for this study:

1) Each profile/sample was considered a point measurement of that particular soil body in space. This ensured that the observed values, *e.g.* field bulk density (FBD), did not include uncertainties due to spatial variability.

2) A general goal was to restrict samples to nonsaline soils.

3) Gravel larger than 6 mm diameter was considered a complicating factor, and was not

included in the survey. Therefore, only soils containing less than an arbitrary 10% coarse material were sampled.

4) Soils representative of the following broad soil classification groups were sampled (MacVicar *et al.*, 1977; Ellis *et al.*, 1979):

a) Red and yellow mesotrophic to distrophic apedal soil forms, *e.g.* Hutton, Clovelly, Avalon, Oakleaf (for Soil taxonomy names, please refer to Table 4.1).

b) Residual soils, *e.g.* Glenrosa.

c) Relatively wet and hydromorphic soils, *e.g.* Westleigh, Pinedene, Katspruit.

d) Grey coloured sands, *e.g.* Fernwood, Longlands, Estcourt.

e) Alluvial soils, *e.g.* Dundee, Oakleaf.

5) The soils selected for this survey included soils that are known to vary in their severity of compaction as well as those soils that are known not to have compaction problems.

6) Only soils with a known management history were sampled.

7) It was strived to collect a broad textural range, as well as to include different textures of the same soil form or at least of the same diagnostic horizon.

8) Finally, four adjacent soil profiles within 75 m distance of each other, but with morphologically different properties (Oakleaf leeufontein, Hutton hutton, Clovelly griffin, Longlands vaalsand) were sampled intensively.

Based on these criteria, 71 samples were collected in the Western Cape (54 samples at Stellenbosch, Paarl, Wellington, Franschhoek and Piketberg), Northern Cape (3 samples at Upington), Northwestern Cape (1 sample at Lutzville), Southwestern Cape (6 samples at Oudtshoorn and Ladismith) and Ceres (7 samples). The sampling locations are shown on the map of the RSA in Map 4.1 on p. 4.54. For practical reasons a total of only 50 soil profiles, from which 71 samples were taken, were investigated. The origin, and background information of each of these samples are listed in Appendix 1.

After removal of any organic debris on the soil surface, bulk samples of 50 kg each of the selected horizons were taken from the open profile pits. In cases where a definite compacted layer was present, the soils were sampled on a depth basis corresponding to the problem layer. For 16 profiles two or more horizons were sampled whereas in others either the top- or subsoil was sampled depending on the morphology, root distribution and management history of a particular soil. Selected morphological properties of the sample population are given in Table 4.1.

Soils were sampled during winter when the water contents were just below field water capacity. Special care was taken not to disturb the natural aggregates. The soils were allowed to dry enough so as not to adhere to the screen, and then carefully sieved by hand through the 6 mm rectangular openings of a 1 $m^2$ stainless steel sieve. The soils were then allowed to get air-dried before subsamples were taken with a sample splitter. One subsample was ground in a rotating mixing drum while being sieved through the 2 mm rectangular openings in the sides of the drum. At this stage eight 2 kg subsamples from the <6 mm diameter soil were drawn for determination of Proctor maximum bulk densities (MBD).

### 4.2.2 Field data collection

Dry soil bulk density (BD) was determined in triplicate at each sampling site with *ca.* 0,30 $dm^3$ steel cylinders. Then ten replicate PSS readings were taken at the sampling site adjacent to the position where BD samples were taken. An automatic recording penetrometer with a constant penetration rate of 1,83 m $min^{-1}$ and interchangeable $30^0$ included-angle, polished steel cones with base areas of 3,23 and 1,29 $cm^2$ was used. Undisturbed soil samples in 0,069 $dm^3$ brass cylinders were taken for water retention determinations using the ceramic plate method (Soil Survey Staff, 1982).

Roots were excavated meticulously and painted white for photography. This was a time-consuming, but effective technique (Schulte-Karring, 1976; Saayman, 1982; Van Huyssteen, unpublished data) in identifying patterns of root growth.

### 4.2.3 Analytical methods

Every sample was analysed in duplicate. Regular checks were included for each batch of samples in the laboratory.

a) <u>Chemical</u>: Routine V.O.R.I. (Viticultural and Oenological Research Institute) techniques were employed for soil chemical analysis. A brief description of the methods is outlined below.

pH: It was determined in a suspension of 4,0 g of soil in 10,0 ml of 1 *M* KCl using a combined glass/calomel electrode.

Resistance ($\Omega$): The resistance of a saturated soil/water paste was determined in the USDA soil cup.

P & K: The method described by Bray and Kurtz (1945) as adjusted by the V.O.R.I. was used to determine Bray2 P and K.

Extractable cations: Na, K, Ca and Mg were extracted with 1 *M* $NH_4Cl$ solution adjusted to the soils' pH and then determined spectrometrically.

CEC: Following the determination of the extractable cations, the $NH_4^+$-saturated soils were washed free of excess salt with alcohol and when chloride free washed again with a 10% solution of NaCl. The displaced nitrogen was then determined in the filtrate by means of an Auto Analyser.

$H^+$: Extractable hydrogen was determined by extraction with $K_2SO_4$, adjusted to pH = 7,0, and titration of the filtrate to pH = 8,0 with NaOH. It was only determined on soils having a pH (1*M* KCl) <5,0.

Exchangeable $Al^{+3}$(acidity): The extraction was done with 1 *M* KCl and colour development in the filtrate was brought about by adding 0,2 g per 100 ml Ferron in water solution. The colour was read at 370 nm on a spectrophotometer. This determination was only done on soils with a pH (1 *M* KCl) <5,0.

Organic carbon: The organic material was determined according to the Walkley-Black method (Allison, 1965). Conversion from organic carbon to organic matter (OM) was done with the Van Bemmelen factor of 1,724.

T-value: Two T-values were calculated: TH, as the sum of extractable cations plus extractable $H^+$, whereas TAl is the sum of extractable cations plus exchangeable $Al^{+3}$. Some researchers (Kamprath, 1970; Juo *et al.*, 1976; Guadalix *et al.* , 1988) regarded either TH or TAI as an effective CEC. The CEC was subsequently adjusted for the percentage of clay content of the sample. The parameter so obtained ($CEC_{clay}$) might give an indication of the clay type.

Lime requirement (LR): Lime required to raise the soil pH (1 *M* KCl) to 5,5 was determined on soils with pH's <5,5 according to the standard V.O.R.I. method adapted from Eksteen (1969).

b) Physical: Most of the physical analytical procedures appropiate to this dissertation are outlined as follows:

Particle size analysis (PSA): It was determined by the principles described by Day (1965). The silt and clay fractions were determined hydrometrically (Van der Watt, 1969), while the sand fractions were determined by dry sieving to separate the soil in the following fractions: coarse sand (2,0-0,5 mm), medium sand (0,5-0,25 mm), fine sand (0,25-0,106 mm), very fine sand (0,106-0,053 mm), coarse silt (0,053-0,02 mm), fine silt (0,02-0,002 mm), clay (<0,002 mm). The 2 to 6 mm fraction was determined by washing a separate <6 mm subsample on a 2 mm sieve. Parallel to the PSA, 300 g of soil was used to further fractionate the sand fraction. Following, (i) the removal of organic matter with $H_2O_2$ and dispersion with sodium hexametaphosphate/$Na_2CO_3$, and (ii) the successive cycles of sedimentation and siphoning to remove suspended clay and silt, the sand fraction was separated by sieving. All size fractions were determined individually and none was estimated by difference. The coarse sand was split into 2 to 1 mm and 1,0 to 0,5 mm fractions; the medium sand into 0,5 to 0,3 mm and 0,3 to 0,25 mm fractions; the very fine sand into 0,106 to 0,075 mm and 0,075 to 0,053 mm fractions. The results compared exactly with the PSA data. Totals were required to be between 97% and 104%. Silt and clay percentages only were used to determine the textural classes with the aid of textural triangles.

The PSA data on a basis <2 mm are summarised in Appendix 2. The PSA data were adjusted for the 2 to 6 mm size fraction (gravel) and are expressed on a <6 mm diameter basis in Appendix 3. The next step in the description of the particle size distribution of the soils was to draw cumulative curves, which are presented in Appendix 4. The x-axis of these curves are expressed in the phi ($\phi$) scale, where $\phi = -\log_2$(diameter in mm), as described by Krumbein and Pettijohn (1938).

Maximum bulk density (MBD): This determination was done according to the method described by Felt (1965) using the following: 100 mm diameter cylinder; 450 mm drop of 2,5 kg hammer; 34 blows per layer which gave an energy of 1 132,2 $m^2\,kg\,s^{-2}$ per sample when compacted in three layers. Samples were prepared to cover the complete range of water contents from air-dry up to the maximum that each sample could hold. Subsamples <6 mm diameter were used, and the same sample was never used again, *i.e.* every compaction test was started with undisturbed aggregates. The curves in the plots presented in Appendix 5 were fitted by the technique of least squares and were used to determine maximum dry bulk density and critical water content.

Modulus of rupture (MOR): It was determined in sixfold following the technique described by Richards (1953) on the fraction <2 mm diameter. One set of determinations was done with one hour soaking time in the frames (MOR1), and another set after 12 hour soaking time as a saturated soil/water paste (MOR2). The samples for the latter determination were molded in the frames only after the soaking time was expired.

Porosity: Total porosity was calculated for both maximum bulk density and field measured bulk density using the formula given by Vomocil (1965). Data for pore size fraction distribution were determined in pressure plate extractors according to the method described by Wourtsakis (1971).

Relative compaction: Field measured bulk density (FBD) was also expressed as relative compaction (RC), applying the equation

$$RC(\%) = \frac{\text{Field measured dry bulk density} \times 100}{\text{maximum dry bulk density}} \cdot$$

Particle density: The particle density of the total soil fraction <2 mm, as well as those of the different size fractions separated by dry sieving, were determined by the method described by Blake (1965). The data are presented in Appendix 6.

Maximum bulk densities of the different size fractions: The maximum bulk density of each fraction, except the 2 to 6 mm fraction, was obtained by vibrating the fraction of known mass for 10 min. in a 50 ml conical centrifuge glass tube at an amplitude of 1,0 mm on a Fritsch Analyzette sieve shaker. During vibration, a perspex weight of 3 g was placed on each sample to keep the surface flat and which also facilitated the volume reading on the precision scale. The 2 to 6 mm fraction was vibrated at the same energy but into 200 ml containers. The results are given in Appendix 7.

Aggregate stability percentage (ASP): This was done by determining the fine silt + clay fraction (<0,02 mm diameter) both in a dispersed and undispersed sample. The undispersed sample was prepared by weighing 60 g of air-dry soil into a Bouyoucos cylinder. It was then carefully filled with distilled water, allowed to soak for 15 minutes, and then shaken 20 times end over end for 40 seconds before the silt + clay reading was taken with a hydrometer at the predetermined sedimentation time. ASP was calculated with the following formula:

$$\mathrm{ASP}(\%) = \frac{100[(\%\ \text{dispersed fraction}) - (\%\ \text{undispersed fraction})]}{(\%\ \text{dispersed fraction})}.$$

The results are given in Appendix 8.

Aggregate stability (AS): This was determined in duplicate using the modified wet-sieving technique (Yoder, 1936) with a nest of 200 mm diameter sieves with rectangular openings of 2,00; 1,00; 0,50; 0,25 and 0,10 mm. The sieving apparatus had a vertical stroke of 38 mm at a rate of 30 strokes per min. For each sample 200 g of air-dry <6 mm diameter soil was placed on the 2 mm sieve, allowed to soak for 10 min. and wet-sieved for 30 min. The soil material remaining on each sieve was oven-dried at 105$^0$C for 12 hours, weighed, and mechanically dispersed as for PSA determinations. Thereafter it was sieved through the same nest of sieves to determine the size distribution of the sand fraction. The formula Hillel (1980) used to calculate the percentage of water-stable aggregates ($AS_i$) is as follows

$$AS_i = \frac{100 \times (M_{soil,i} - M_{sand,i})}{(M_{soil,t} - M_{sand,t})}$$

where, $M_{soil,i}$ is the total mass of oven- dry soil retained after wet sieving for the *ith* fraction, $M_{sand,i}$ is the oven-dry weight of the sand for the *ith* fraction, $M_{soil,t}$ is the total mass of the whole soil sample, and $M_{sand,t}$ is the mass of sand in the whole soil sample. Aggregate mean weight diameter (MWD) was calculated according to Reeve (1965) by

$$\mathrm{MWD} = \left(\sum_{i=1}^{n} x_i w_i\right) \Big/ \sum_{i=1}^{n} w_i$$

where, $x_i$ is the mean diameter of the *ith* aggregate fraction, $w_i$ is the total mass of the sample. Geometric mean diameter (GMD) was calculated (Reeve, 1965) by

$$GMD = \exp\left[\left(\sum_{i=1}^{n} w_i \log(x_i)\right) \Big/ \sum_{i=1}^{n} w_i\right].$$

The results are summarised in Appendix 8.

Air-to-water permeability ratio (AWR): Air and water permeabilities of artificially packed soils were determined using the method described by Reeve (1953, 1965). The samples were duplicated for this determination. Twenty eight percent of the samples (20) had to be repeated because the two replicates differed by more than 10%. Transparent plastic bottles with a height of 80 mm and an internal diameter of 55 mm, each with five 5 mm holes in the bottom, were used as permeameters. A nylon mesh disc on the bottom retained the soil, while allowing free passage of air and water through the holes in the bottom of the containers. Dry soil (<2 mm $\phi$) was carefully poured through a funnel into the permeameter so that aggregate segregation was minimal. A 250 g weight was placed on the soil, while it was vibrated at an amplitude of 1,5 mm for 30 seconds to pack the soil.

The falling pressure head technique was used to determine permeability to air. Permeability to water was determined on the same sample after deionised water had percolated for four hours through the sample. Deionised water was used throughout to minimise the effect of different water qualities on the permeability of the soils. A constant hydraulic head was used for water permeability measurements. The following formulae were applied for calculations (Reeve, 1965):

a) Air permeability $= K'_a = \dfrac{nQ}{A(\Delta p)/L}$ ($cm^2$) where,

| | | |
|---|---|---|
| n | = | viscosity of air ($g\ s^{-1}\ cm^{-1}$) |
| Q | = | flow rate ($cm^3\ s^{-1}$) |
| A | = | cross sectional area of the soil column ($cm^2$) |
| $\Delta p$ | = | pressure difference ($g\ cm^{-1}\ s^{-2}$) |
| L | = | length of soil column (cm). |

b) Hydraulic conductivity = $K = \dfrac{VL}{A(\Delta h)(\Delta t)}$ $(cm\ s^{-1})$ where,

| | | |
|---|---|---|
| $V$ | = | volume of percolate in time $\Delta t$ $(cm^3)$ |
| $L$ | = | length of soil column (cm) |
| $A$ | = | cross sectional area of soil column $(cm^2)$ |
| $\Delta h$ | = | hydraulic head difference between inflow and outflow ends of soil column (cm) |
| $\Delta t$ | = | time interval for volume of percolate (V) to pass through the soil (s). |

c) Water permeability = $K'_w = \dfrac{nK}{\rho_w g}$ $(cm^2)$ in which,

| | | |
|---|---|---|
| $K$ | = | hydraulic conductivity $(cm\ s^{-1})$ |
| $n$ | = | viscosity of water at the recorded temperature $(g\ s^{-1}\ cm^{-1})$ |
| $\rho_w$ | = | density of water $(g\ cm^{-3})$ |
| $g$ | = | acceleration of gravity $(cm\ s^{-2})$. |

<u>Note</u>: Values for n, $\rho_w$ and g were obtained from the Handbook of Chemistry & Physics. 62nd ed., 1981-1982.

## 4.3 RESULTS AND DISCUSSION

For ease of reference throughout this dissertation a number of data tables and figures is presented in the Appendix, the contents of which will be discussed in more detail in subsequent chapters. In this chapter the observed rooting patterns at the sampling sites and the occurrence of specific compacted or loose layers are discussed.

### 4.3.1 Sample description

Selected morphological properties of the soils sampled for compaction studies are given in Table 4.1. The percentage spread within the three main particle size classes (<2,0 mm basis) is presented in Figure 4.1a and is as follows

| | |
|---|---|
| clay (<0,002 mm) | 1,17 - 37,63% |
| silt (0,002 - 0,053 mm) | 2,25 - 46,65% |
| sand (0,053 - 2,0 mm) | 33,96 - 95,40%. |

The sandgrades expressed as a percentage of the total sand fraction (<2 mm basis) are presented in Figure 4.1b and ranged as listed below

| | |
|---|---|
| fine sand (0,053 - 0,25 mm) | 9,66 - 98,16% |
| medium sand (0,25 - 0,50 mm) | 1,18 - 41,08% |
| coarse sand (0,50 - 2,00 mm) | 0,32 - 74,79%. |

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Particle size analysis showed that the sample population satisfied the prerequisites about soil type and texture mentioned earlier in this chapter. The fact that no silt loams, silt clay loams, silty clays, clays and only a few sandy clays were included in the sample population (Fig. 4.1a) was because these textural groups are not important for grapevine growing and is not a shortcoming of the sampling procedure.

The chemical results are given in Table 4.2. The samples generally had low pH values (except for the alluvial soils from the hot and dry irrigation areas); were low in organic matter; and had non-swelling clays as indicated by the generally low cation exchange capacity (CEC) and effective exchange capacity ($CEC_{clay}$) values. It can be safely stated that, except maybe for sample no. 50, high salt content (measured as resistance) was not responsible for any of the compaction problems reported in this study.

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Except for the samples from Upington, Oudtshoorn and Lutzville (Map 4.1 on p. 4.54), all the soils were subjected to high winter rainfall amounts and periodic summer droughts under a typical Mediterranean climate. The practical experience with soils under such conditions, and having properties as outlined above, indicates that once a compacted layer has developed, it can only be ameliorated by mechanical means.

In Table 4.3 selected physical soil properties of the sample population are presented. It also serves as a background to the visual documentation of compaction and PSS measurements reported in this chapter. The data in Table 4.3 will be discussed in Chapter 5. At this stage it will suffice to summarise Table 4.3 by reporting the ranges for selected variables

| | |
|---|---|
| maximum bulk density | 1,600 - 2,080 Mg $m^{-3}$ |
| field bulk density | 1,269 - 2,042 Mg $m^{-3}$ |
| modulus of rupture (one hour) | 0 - 147,6 kPa |
| modulus of rupture (12 hours) | 4,3 - 463,9 kPa |
| relative compaction | 69,5 - 107,8%. |

Note: It was hypothesised that the modulus of rupture value determined on a saturated soil-water paste after twelve hours soaking (MOR2) will give an indication of the tendency of soils to puddle and to set hard during drying. This will be referred to in later discussions.

### 4.3.2 Visual presentation of compaction and root distribution data

The aim of this section is a qualitative presentation of the typical effects of compaction on the grapevine root. Colour plates of selected profiles only are presented (Plate 4.1 - 4.14), which illustrate the many aspects of compaction in the field. (Sample nos. refer to those listed in Appendix 1).

The typical appearance of a healthy, young, growing grapevine root tip as shown in Figure 4.2a was commonly found in this investigation. The young root is fairly thick right at the tip, but is markedly thinner a few centimeters back (Fig. 4.2b), a phenomenon which can be explained by the anatomy of the grapevine root system. The present study confirmed that the cortex consisted of a thick layer of parenchyma cells (Fig. 4.2c) which collapsed when secondary growth commenced (Fig. 4.2d). This cortical collapse takes place a few centimeters behind the growing root tip, which explains the reduction in vine root thickness (Fig. 4.2b). This would suggest that fairly large soil pores are needed for the grapevine root tip to make an initial entry, even though the roots that are generally observed might be thinner because of the cortical collapse.

The qualitative studies of the grapevine roots in the field, as presented by the examples in Plate 4, showed that roots were abruptly and seriously impeded by different types of compaction over a range of soil types. Soil layers responsible for impeding roots could be grouped as follows: natural subsoil compaction; sharp transitions from loose to relatively compact subsoil; dense packing on structureless sandy soils; thin, but practically poreless, smeared surfaces at the bottom of the ploughing depth; and man-made traffic pans. The smeared surfaces proved that even in the field very thin compacted layers would be impenetrable due to their low porosity. The inability of grapevine roots to penetrate a relatively compact layer underlying a loose topsoil could be explained by buckling root strength. The loose soil does not supply enough support to the growing and penetrating root, which will cause the root to buckle or to be deflected when encountering a soil layer of higher density (Dexter and Hewitt, 1978; Whiteley *et al.*, 1982). It was reported by Greacen *et al*. (1969) that as the angle of incidence with the "compacted" layer increases, the pea root penetration decreases. Dexter and Hewitt (1978) reported similar results for wheat roots. → Greacen et al. (1969) het gevind met ertjies, dat wortel penetrasie verminder as die invalshoek met die kompakte laag verhoog.

### 4.3.3 Penetrometer soil strength (PSS)

In Chapter 2 it was shown that a direct linear relationship existed between BD and PSS. Therefore PSS, an easily measurable property, was considered a measure which can be used to describe field soil compaction at the time of sampling. The results reported in Figure 4.3, Table 4.3 and Appendix 4 are discussed in this section.

The results of the PSS measurements are presented in Figure 4.3. Each point on the curves is the mean of ten measurements. From the 17 graphs presented it is clear that considerable differences in PSS existed between different profiles as well as between depths in the same profile. These differences underscore variation in the severity of soil compaction encountered in vineyard soils.

For the interpretation of the PSS data it must be remembered that no critical BD or PSS value above which root penetration was absolutely impeded could be determined for the five soil types used in the pot experiment (Chapter 2). In contrast, there seems to be a critical, albeit ill-defined, soil strength above which root penetration is seriously hindered - generally reported in literature as 2 000 to 2 500 kPa for various crops and penetrometer probes (Zimmerman and Kardos, 1961; Taylor and Gardner, 1963; Taylor and Burnett, 1964; Greacen *et al.*, 1969; Bar-Yosef and Lambert, 1981). On the other hand, Ehlers (1982) found that growth of oat roots was terminated at a PSS of 3 600 kPa and 4 600 to 5 100 kPa on a tilled and untilled loess soil, respectively. These values are higher than the pressure actually exerted by growing roots (Russell and Goss, 1974; Whiteley *et al.*, 1981). Like Dexter (1986a, 1986b), Ehlers (1982) ascribed this phenomenon to root growth along biopores and cracks. This explains the sporadic root penetration into compacted layers observed in the present study, *e.g.* sample no. 63 (Plate 4.13). Presently an arbitrary critical PSS value of 2 000 kPa is accepted by the V.O.R.I.

The PSS for the 100 to 500 mm depth of soil no. 5 (Glenrosa) was just over the critical 2 000 kPa with a maximum at 175 mm (Fig.4.3a) and coincided with a relative compaction of 89,9% (Table 4.3). A good grapevine root distribution was however noted from 200 mm and deeper. The BD (1,820 Mg $m^{-3}$) measurement was made in the middle (300 mm depth) of the sampling depth (0-600 mm). Therefore, the compaction in this example appeared to be a topsoil problem more than a subsoil problem. As this soil was properly mixed in depth by two-direction deep ploughing, there was no distinct topsoil layer (0-300 mm) that differed texturally or morphologically from the underlying layer (300-600 mm). Consequently, it was deduced that the compacted layer is either a traffic pan (a remnant from leveling actions following deep ploughing) or must have formed under the influence of the climate (intensive wetting and drying cycles) or both. The MOR2 value (modulus of rupture after 12 hours soaking time) of 239,99 kPa (Table 4.3) confirmed the observed tendency for this soil to get very hard when dry.

The PSS curves for sample nos. 6 to 9 (Glenrosa, Fig. 4.3b) illustrate that the natural high PSS in the subsoil can be alleviated by deep ploughing. In this case, an adjacent land was deep ploughed three years before the measurements were made, which made this comparisons possible. The previous experience with this soil type was that it would recompact only under wheel traffic (Van Huyssteen, 1983). In this profile, the effect of wheel compaction was measured down to a depth of 550 mm. Roots were not able to penetrate the undisturbed high strength subsoil as is shown in Plate 4.2. The bottom of the plough share smeared the soil on the working depth at 900 mm (Plate 4.3), which effectively impede deeper root penetration (Plate 4.4).

Although not often realised, sandy soils are also subject to compaction as is shown by the curve for the unloosened soil of sample nos. 10 to 12 (Fig. 4.3c). Sample nos. 11 and 12 had relative compaction values of 91,59% and 97,41% (Table 4.3), respectively, which explained the shallow root system of the vineyard, which had to be uprooted due to poor yields. Despite the low MOR2 value (21,1 kPa), sample no. 12 (E horizon) displayed signs of hardsetting when dry, which suggests cementation. The measured decrease in PSS below 500 mm depth was due to wetness as a result of a perched water table on the very dense ( BD = 2,042 Mg $m^{-3}$) underlying clay horizon (Sample no. 13). This high density (relative compaction = 107,8%) was probably due to clay illuviation into the pores and cracks of the subsoil. Although this profile did not recompact to high soil strengths after one wheel trip only (measured directly after deep ploughing), it was interesting to note that the effect, interestingly enough, extended down to a depth of 600 mm (Fig. 4.3c).

Sample no. 19 (Longlands) had a relative compaction of only 83,92% (Table 4.3). It is speculated that it is the slight increase in PSS to just over 2 000 kPa (Fig.4.3d) which almost completely restricted root growth to the topsoil. A possible explanation for this could be that the penetrating root tip could not displace the soil particles in this soil, which had 79% of its particles in the size classes >0,106 mm (phi-number = 2, compare Appendix 4). In addition, this loamy sand had a MOR2 value of 112,2 kPa. Experience has proved this soil to be very sensitive to soil management practices.

The variation in PSS of four adjacent, but morphologically distinct, soils over a distance of 75 m downslope was aptly demonstrated for the Oakleaf (Sample nos. 21-23), Hutton (Sample nos. 24-27), Clovelly (Sample nos. 28-30) and Longlands (Sample nos. 31-33) soils. These soils had never been deep ploughed before and the PSS curves (Fig 4.3e-h) represented the natural state. A tendency for higher soil strengths in the subsoil to occur at shallower depths was observed in the order Oakleaf < Hutton < Clovelly < Longlands in a downslope direction when the 2 000 kPa threshold value is considered. The markedly different soil strengths must have been induced by soil forming processes varying in space according to relief and drainage. The high relative compaction values also indicated that these soils will benefit by deep ploughing (Table 4.3). Furthermore, with the exception of the topsoil of the Hutton (Sample no. 24), the high MOR2 values (>225 kPa), as documented in Table 4.3, signify a tendency for the topsoils to get hard when dry. The clearly higher PSS and BD values in the 100 to 325 mm depth layer of the Longlands soil (Sample no. 31) probably indicate a ploughpan (Table 4.3). The reason why a ploughpan developed in this specific sandy clay loam, and not in the three adjacent, similarly managed topsoils of the same textural class (Sample nos. 21, 24 and 28 in Fig. 4.3e, f and g, respectively) is not exactly clear, but it may be due to the wet soil conditions prevailing in this profile. However, compared on the basis of particle size distribution data (<2 mm basis), sample no 31 had the highest coarse sand (28,7%) and lowest silt + clay (34,7%) contents and a slightly higher kurtosis value (2,70) compared to the three mentioned topsoils (Appendices 2 and 9). The effects on soil compaction of genetical/chemical soil characteristics in this toposequence of soils should be further investigated.

Low PSS values were recorded for sample nos. 34 and 35 (Estcourt) as illustrated in Figure 4.3i. This soil type is however known to form root impeding layers, probably because the penetrating root tip cannot displace individual soil particles even at low PSS values. Although it has a lower kurtosis value (3,5) than sample no. 19 (7,9), but similar MOR2 values (112-123 kPa), this soil has the same management problems as the mentioned Longlands vasi (Sample no. 19) in the field (Table 4.3; Appendix 9).

The Oakleaf soil represented by nos. 36 to 39 in Figure 4.3j had varying PSS values with depth in the natural unloosened state. Like the variations in the case of sample nos. 21 to 33 (Fig. 4.3e-h) this must have been the result of natural soil forming processes. No lithological discontinuities were obvious from the particle size data (Appendices 2 and 3) and the cumulative PSA curves in Appendix 4 as the sand- and silt-sized fractions were relatively constant with depth (Washer and Collins, 1988). These four samples were included in the study to determine whether they will recompact to different degrees once they have been loosened.

The PSS for sample nos. 53 and 54 portrayed a condition often found on soils like the Clovelly, which otherwise have a high potential for growing grapevines (Plate 4.11). The characteristic sharp increase in PSS occurred at the bottom of the ploughing depth (Fig. 4.3k). As no smeared surface was observed, root impedance must have been due to the unwanted sharp transition from low to high PSS and/or to natural subsoil compaction (Plate 4.11).

The increase in fine sand (10,8-24,3%) from sample no. 57 to sample no. 58 (Appendices 2 and 4) probably was enough to practically stop root penetration and to cause the increase in PSS (Plate 4.12; Fig. 4.3l). This was associated with a decrease (20,69-14,96%) in the slow draining coarse pores (50-10 $\mu$m) and a BD of 1,550 Mg $m^{-3}$ compared to the 1,467 Mg $m^{-3}$ of the overlying horizon (Sample no. 57). The other pore size classes were not affected to the same extent (data not shown).

The high soil strengths and BD's that are sometimes measured on sandy loams are illustrated for a Clovelly soil (Sample nos. 60 and 61) in Figure 4.3m. Sample no. 62 (Fernwood loamy sand) is another example of high compaction in the subsoil in the natural state, and also of the sharp transition from loose to compacted soil at the working depth (Fig. 4.3n).

In Figure 4.3o an example of the PSS measured in a traffic pan is illustrated, in this case from 150 to 350 mm depth. Roots could not penetrate through the traffic pan (Sample no. 63) to the loose and gravelly subsoil (Plate 4.13). The higher soil strengths deeper than 500 mm were due to a high gravel content (> 20% m/m) which did not occur in the measured layer.

Sample no. 66 (loamy sand) is representative of a group of vineyard soils that are difficult to manage. Although grapevine roots were impeded (Plate 4.14), no definite compacted layer relative to the topsoil could be found (Fig. 4.3p). Only a gradual increase in soil strength was observed. The 100 to 400 mm depth had a relative compaction of 91,7% at a FBD of 1,963 Mg $m^{-3}$. The reason for this high BD was not clear because this soil has 77,4% of its particles in the <0,106 mm size class (Appendix 4) and has a kurtosis value of 5 (<6 mm basis) as reported in Appendix 9. Kurtosis is a measure of the grading of soils. Higher coefficients of kurtosis point to heavier tails than for a normal distribution and were previously reported to be associated with lower BD's (Moolman, 1981). However, such a gradual increase in PSS with depth, coupled with poor root penetration, was often measured for loamy sands (Van Huyssteen, unpublished data).

Very high PSS values were measured on the vineyard soil represented by sample no. 71, which 15 years previously had been ploughed to a depth of 450 mm (Fig. 4.3q). These high soil strengths must have been due to excessive wheel traffic in the vineyard because this soil type is generally considered to be stable against recompaction.

### 4.3.4 Porosities

It is common knowledge in soil science that compaction of sandy soils affects the pore size distribution in the larger pore size range more than in the fine size range. This was previously illustrated by Van Huyssteen and Weber (1980) for a Clovelly sandy clay loam soil. In Figure 4.4 the pore size classes for both the "compacted" and "loose" Oakleaf soil represented by sample nos. 49 to 52 are shown, which illustrates the general statement made above. The topsoil of the problem site (Sample 49) had less coarse pores than the topsoil from the nonproblem area (Sample 51). The low pecentages of very fast draining coarse pores (VFDCP) and fast draining coarse pores (FDCP) explained the water infiltration problems encountered on this soil (Sample 49). The same results were also obtained for other soils in the sampling population but the data are not presented. (In the case of clay or silt soils the effect of compaction on the smaller pores may be more pronounced (Hill and Sumner, 1967)).

In general, it can be stated that, as a result of increasing BD a smaller number of coarse pores is left for the fairly thick, growing grapevine root tips to make an initial penetration. Together with the decrease in coarse pores, PSS will increase, which implies that root tips would need more energy to force their way into the compacted soil or may even be stopped from further penetration once they have made the initial entry.

## 4.4 SUMMARY AND CONCLUSIONS

Two factors have emerged out of this study as important in developing management practices for grapevines.

1) Soil compaction can retard and even impair root development. Therefore, the quality of the rooting medium, *i.e.* low BD's and low PSS throughout the profile, is vitally important for optimum root growth.

2) Soil compaction has many facets and may vary in severity. Even klein subtle changes in soil properties, *e.g.* increase in fine sand, can cause marked changes in BD and rooting patterns.

These two observations suggest that better techniques are needed to extrapolate data from controlled soil management experiments and compactibility studies to real world field situations. Additionally, the prediction of compactibility on a routine basis is needed for sound decision-making on soil management practices. Any approach to predictions of compactibility must involve understanding of the problem in the field and the measurement of basic soil properties.

Rooting patterns were found to be direct indicators of compaction in the areas investigated. Admittedly, under high rainfall conditions and/or on low-lying hydromorphic soils, water infiltration, the presence of a water table and reduced oxygen availability may also determine rooting patterns. Root studies should consequently be complementary to any physical measurement when undertaking compactibility studies. In fact, this might be the only method to define root growth limiting BD's for different crops and different soils. As shown earlier in a pot experiment (Chapter 2), plus the results of Grimes *et al.* (1982) for plum trees and those of Saayman (1982) for vineyards, this study confirms that the grapevine root is seldom completely impeded by highly compacted subsoils. As indicated by Nicolosi and Fretz (1980), the complex interactions between physical properties of the soil affecting root growth make it nearly impossible to assign oortuigend conclusive significance to individual factors. Nevertheless it could be concluded that mechanical impedance and reduced porosity, as expressed by BD, are significant factors in causing abnormal root growth.

Natural high densities in undisturbed soils, especially in the subsoil, are a problem throughout the viticultural areas. In addition, either man-made (compression) or natural (structural collapse) recompaction can undo the positive effects of expensive deep ploughing operations that were initially applied to do away with soil compaction. A major problem is that recompaction is not always recognised as soil compaction, *e.g.* gradual increases in PSS on loamy sands (*e.g.* Fig. 4.3p; Plate 4.14).

The soil samples collected should be used as a starting point to develop a quantitative basis for a better understanding and description of the compaction problem in vineyard soils by applying prediction techniques based on permanent soil characteristics.

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Table 4.1. Selected morphological properties of the soils sampled for compaction studies.

| Sample no.[a)] | Soil classification: Form[b)] | Soil classification: Serie[b)] | Soil classification: Soil taxonomy[c)] | Horizon | Depth (mm) | Texture[d)]: Sand-grade | Texture[d)]: Class | Colour[e)]: Dry | Colour[e)]: Wet |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Dundee | Dundee | Fluvent | - | 200-450 | F | LSa | 7.5 YR 5/4 Br | 10 YR 4/3 Br |
| 2 | Westleigh | Langkuil | Plinthoxeralf | A + B21 | 0-800 | C | LSa | 10 YR 6/1 Gr | 10 YR 4/2 dk Gr Br |
| 3A | Westleigh | Rietvlei | Plinthoxeralf | A | 0-300 | F | L | 10 YR 5/1 Gr | 10 YR 3/1 vdk Gr |
| 4A | Westleigh | Westleigh | Plinthoxeralf | B21 | 300-650 | F | SaL | 10 YR 8/1 W | 10 YR 6/1 Gr |
| 5 | Glenrosa | Williamson | Haploxeralf | A + B21 | 0-600 | F | SaClL | 10 YR 7/6 Y | 10 YR 5/8 Y Br |
| 6B | Glenrosa | Robmore | Haploxeralf | A | 0-300 | C | SaL | 10 YR 6/4 lt Y Br | 10 YR 4/3 Br |
| 7B | Glenrosa | Robmore | Haploxeralf | B21 | 300-700 | C | ClL | 10 YR 6/4 lt Y Br | 10 YR 3/3 dk Br |
| 8B | Glenrosa | Robmore | Haploxeralf | B22 | 700-1300 | C | ClL | 10 YR 6/4 lt Y Br | 10 YR 4/6 dk Y Br |
| 9B | Glenrosa | Robmore | Haploxeralf | C | 1300-1600 | C | L | 10 YR 8/4 vp Br | 10 YR 5/8 Y Br |
| 10C | Longlands | Tayside | Plinthoxeralf | Ap | 0-250 | C | Sa | 10 YR 5/3 Br | 10 YR 5/4 Y Br |
| 11C | Longlands | Tayside | Plinthoxeralf | A | 250-400 | C | Sa | 10 YR 6/4 lt Y Br | 10 YR 4/6 dk Y Br |
| 12C | Longlands | Tayside | Plinthoxeralf | E | 400-850 | C | Sa | 10 YR 6/4 lt Y Br | 10 YR 5/8 Y Br |
| 13C | Longlands | Tayside | Plinthoxeralf | B21 | 850-1200 | C | SaClL | 10 YR 6/4 lt Y Br | 10 YR 5/8 Y Br |
| 14D | Katspruit | Killarney | Typic Haplaquept | A | 0-320 | F | L | 10 YR 6/1 Gr | 10 YR 4/2 dk Gr Br |
| 15D | Katspruit | Killarney | Typic Haplaquept | A12 | 320-650 | F | L | 10 YR 6/1 Gr | 10 YR 4/2 dk Gr Br |
| 16D | Katspruit | Killarney | Typic Haplaquept | G | 650-900 | F | L | 10 YR 6/4 lt Y Br | 10 YR 5/4 Y Br |
| 17E | Westleigh | Paddock | Plinthoxeralf | A12 | 250-650 | C | L | 10 YR 5/3 Br | 10 YR 3/3 dk Br |
| 18E | Westleigh | Paddock | Plinthoxeralf | B21 | 650-900 | C | SaL | 10 YR 5/3 Br | 10 YR 4/2 dk Gr Br |
| 19 | Longlands | Vasi | Plinthoxeralf | A + E | 0-500 | M | LSa | 10 YR 6/4 lt Y Br | 10 YR 5/4 Y Br |
| 20 | Fernwood | Maputa | Xeropsamment | B | 300-800 | C | Sa | 10 YR 8/4 vp Br | 10 YR 7/6 Y |
| 21F | Oakleaf | Leeufontein | Xerochrept | A | 0-250 | F | SaClL | 7.5 YR 5/4 Br | 7.5 YR 4/6 str Br |
| 22F | Oakleaf | Leeufontein | Xerochrept | B21 | 250-550 | F | SaCl | 7.5 YR 6/6 RY | 5 YR 4/6 YR |
| 23F | Oakleaf | Leeufontein | Xerochrept | B22 | 550-1100 | F | SaCl | 7.5 YR 6/6 RY | 5 YR 4/6 YR |
| 24G | Hutton | Hutton | Palexeralf | A | 0-400 | C | SaClL | 7.5 YR 5/4 Br | 7.5 YR 4/6 str Br |
| 25G | Hutton | Hutton | Palexeralf | B21 | 400-700 | C | SaCl | 7.5 YR 5/8 str Br | 5 YR 4/6 YR |
| 26G | Hutton | Hutton | Palexeralf | B22 | 700-1100 | C | SaClL | 7.5 YR 6/6 RY | 7.5 YR 5/8 str Br |
| 27G | Hutton | Hutton | Palexeralf | C | 1100-1300 | C | SaClL | 10 YR 7/6 Y | 7.5 YR 5/8 str Br |
| 28H | Clovelly | Griffin | Palexeralf | A | 0-300 | C | SaClL | 7.5 YR 6/6 RY | 7.5 YR 4/6 str Br |
| 29H | Clovelly | Griffin | Palexeralf | B21 | 300-750 | C | SaCl | 7.5 YR 5/8 str Br | 5 YR 4/6 YR |
| 30H | Clovelly | Griffin | Palexeralf | C | 750-1000 | C | SaCl | 10 YR 7/8 Y | 7.5 YR 5/8 str Br |

(continued on next page)

Table 4.1. Continued.

| Sample no.[a] | Soil classification | | | Horizon | Depth (mm) | Texture[d] | | Colour[e] | |
|---|---|---|---|---|---|---|---|---|---|
| | Form[b] | Serie[b] | Soil taxonomy[c] | | | Sand-grade | Class | Dry | Wet |
| 31I | Longlands | Vaalsand | Plinthoxeralf | A | 0-350 | C | SaClL | 10 YR 6/4 lt Y Br | 7.5 YR 4/6 str Br |
| 32I | Longlands | Vaalsand | Plinthoxeralf | E | 350-750 | C | SaClL | 7.5 YR 6/6 RY | 7.5 YR 5/8 str Br |
| 33I | Longlands | Vaalsand | Plinthoxeralf | B21 | 750-900 | C | SaCl | 10 YR 7/6 Y | 10 YR 5/8 Y Br |
| 34J | Estcourt | Uitvlugt | Natrixeralf | A | 0-450 | M | SaL | 10 YR 6/1 Gr | 10 YR 3/3 dk Br |
| 35J | Estcourt | Uitvlugt | Natrixeralf | A12 + E | 450-850 | M | SaL | 10 YR 6/1 Gr | 10 YR 4/6 dk Y Br |
| 36K | Oakleaf | Leeufontein | Xerochrept | A | 0-250 | F | SaL | 7.5 YR 5/4 Br | 5 YR 3/4 dk R Br |
| 37K | Oakleaf | Leeufontein | Xerochrept | B21 | 250-550 | F | SaClL | 7.5 YR 5/8 str Br | 5 YR 4/6 YR |
| 38K | Oakleaf | Leeufontein | Xerochrept | B22 | 550-900 | F | SaClL | 5 YR 5/6 YR | 5 YR 4/6 YR |
| 39K | Oakleaf | Leeufontein | Xerochrept | C | 1000-1200 | F | SaClL | 10 YR 7/8 Y | 5 YR 4/6 YR |
| 40 | Clovelly | Clovelly | Palexerult | B21 | 400-700 | F | SaCl | 10 YR 7/8 Y | 7.5 YR 5/8 str Br |
| 41 | Dundee | Dundee | Fluvent | A | 0-400 | F | L | 10 YR 5/3 Br | 5 YR 3/3 dk R Br |
| 42L | Westleigh | Langkuil | Plinthoxeralf | A | 0-300 | M | LSa | 10 YR 6/1 Gr | 10 YR 3/2 vdk Gr Br |
| 43L | Westleigh | Langkuil | Plinthoxeralf | A12 | 300-700 | C | LSa | 10 YR 8/4 vp Br | 10 YR 5/4 Y Br |
| 44 | Hutton | Hutton | Palexerult | B21 | 300-900 | C | SaClL | 10 YR 7/8 Y | 7.5 YR 5/8 str Br |
| 45 | Longlands | Tayside | Plinthoxeralf | A + E | 150-600 | C | Sa | 10 YR 6/1 Gr | 10 YR 4/2 dk Gr Br |
| 46 | Longlands | Tayside | Plinthoxeralf | A + E | 150-600 | C | Sa | 10 YR 6/4 lt Y Br | 7.5 YR 4/6 str Br |
| 47 | Avalon | Wolweberg | Plinthudult | A + B21 | 0-850 | C | SaL | 10 YR 6/4 lt Y Br | 10 YR 4/6 dk Y Br |
| 48 | Estcourt | Estcourt | Natrixeralf | A12 | 250-700 | C | SaClL | 10 YR 8/4 vp Br | 10 YR 7/8 Y |
| 49M | Oakleaf | Jozini | Haploxeralf | Ap | 0-300 | F | SaL | 10 YR 6/4 lt Y Br | 10 YR 3/6 dk Y Br |
| 50M | Oakleaf | Jozini | Haploxeralf | B21 | 300-700 | F | ClL | 10 YR 6/4 lt Y Br | 10 YR 4/6 dk Y Br |
| 51N | Oakleaf | Jozini | Haploxeralf | Ap | 0-300 | F | SaL | 10 YR 5/3 Br | 10 YR 3/6 dk Y Br |
| 52N | Oakleaf | Jozini | Haploxeralf | B21 | 300-700 | F | SaClL | 10 YR 5/3 Br | 5 YR 3/4 dk R Br |
| 53O | Clovelly | Oatsdale | Xerochrept | A | 0-400 | C | SaL | 10 YR 7/8 Y | 7.5 YR 5/8 str Br |
| 54O | Clovelly | Oatsdale | Xerochrept | B21 | 400-900 | C | SaL | 10 YR 5/4 Y Br | 10 YR 3/6 dk Y Br |
| 55 | Pinedene | Eykendal | Haploxerult | B21 | 150-400 | C | LSa | 10 YR 6/1 Gr | 10 YR 4/3 Br |
| 56P | Dundee | Dundee | Fluvent | - | 0-250 | F | L | 10 YR 4/3 Br | 10 YR 3/2 vdk Gr Br |
| 57P | Dundee | Dundee | Fluvent | - | 250-400 | F | SaL | 10 YR 5/3 Br | 5 YR 3/4 dk R Br |
| 58P | Dundee | Dundee | Fluvent | - | 400-700 | F | SaL | 10 YR 4/3 Br | 10 YR 3/2 vdk Gr Br |
| 59 | Clovelly | Oatsdale | Palexerult | A | 150-350 | F | SaL | 10 YR 5/4 Y Br | 10 YR 3/3 dk Br |
| 60Q | Clovelly | Vidal | Palexerult | A | 0-250 | F | SaL | 10 YR 5/4 Y Br | 7.5 YR 4/6 str Br |

(continued on next page)

Table 4.1. Continued.

| Sample no.[a)] | Soil classification: Form[b)] | Serie[b)] | Soil taxonomy[c)] | Horizon | Depth (mm) | Texture[d)]: Sand-grade | Class | Colour[e)]: Dry | Wet |
|---|---|---|---|---|---|---|---|---|---|
| 61Q | Clovelly | Vidal | Palexerult | B21 | 250-400 | F | SaL | 10 YR 5/8 Y Br | 7.5 YR 4/6 str Br |
| 62 | Fernwood | Sandveld | Xeropsamment | A12 | 120-250 | C | LSa | 10 YR 4/2 dk Gr Br | 10 YR 3/2 vdk Gr Br |
| 63 | Pinedene | Betlehem | Haploxerult | A | 150-350 | C | Sa | 10 YR 5/3 Br | 10 YR 4/3 Br |
| 64 | Dundee | Dundee | Fluvent | - | 300-700 | M | LSa | 10 YR 5/3 Br | 5 YR 3/4 dk R Br |
| 65 | Westleigh | Rietvlei | Phlinthoxeralf | A + A3 | 0-600 | F | SaL | 10 YR 5/3 Br | 10 YR 3/2 vdk Gr Br |
| 66 | Pinedene | Betlehem | Palexerult | A + B21 | 100-400 | C | LSa | 10 YR 6/4 lt Y Br | 7.5 YR 4/6 str Br |
| 67 | Katspruit | Katspruit | Typic Haplaquept | A | 0-300 | C | SaClL | 10 YR 6/1 Gr | 10 YR 3/3 dk Br |
| 68 | Avalon | Wolweberg | Phlinthudult | A | 70-200 | C | Sa | 10 YR 6/4 lt Y Br | 10 YR 3/3 dk Br |
| 69 | Clovelly | Lundini | Xerorthent | A | 0-300 | C | Sa | 10 YR 6/4 lt Y Br | 7.5 YR 4/6 str Br |
| 70 | Clovelly | Soweto | Xerorthent | A | 0-300 | C | Sa | 10 YR 6/4 lt Y Br | 10 YR 4/3 Br |
| 71 | Clovelly | Southwold | Xerochrept | A | 0-300 | F | L | 10 YR 6/4 lt Y Br | 7.5 YR 4/6 str Br |

a) Figures followed by the same letter indicate samples taken from the same profile.

b) Soil forms, series and horizon designations from Soil classification - a binomial system for South Africa (MacVicar, *et al.*, 1977).

c) Soil taxonomy names from Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys (Soil Survey Staff, 1975).

d) Symbols used are the same given in Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys (Soil Survey Staff, 1975).

e) Soil colours as in the Soil colour chart. Compiled by the Soils and Irrigation Research Institute, Pretoria, 1951. Designed and produced by Munsell Color, 244IN Calvert St., Baltimore, Md. 21218, U.S.A.

Table 4.2. Chemical analyses* of the soils sampled for compaction studies.

| Sample no. | pH (1M KCl) | Electrical resistance (ohms) | Bray2 P (mg kg$^{-1}$) | Bray2 K (mg kg$^{-1}$) | Extractable cations (cmol(+) kg$^{-1}$soil) Ca | Mg | Na | K | H | T-values (cmol(+) kg$^{-1}$ soil) TH | TAl | CEC (cmol(+) kg$^{-1}$ soil) | Al (cmol(+) kg$^{-1}$ soil) | Org. C (%) | Org. mat. (%) | Lime requirement (t ha$^{-1}$) | CEC$_{clay}$ (cmol(+) kg$^{-1}$ clay) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 5,58 | 1069 | 66,40 | 90,20 | 1,77 | 1,04 | 0,04 | 0,15 | - | 2,99 | 2,99 | 2,74 | - | 0,12 | 0,20 | - | 61,71 |
| 2 | 5,23 | 900 | 105,00 | 53,70 | 0,95 | 0,26 | 0,04 | 0,08 | 0,36 | 1,70 | 1,34 | 1,29 | - | 0,27 | 0,46 | 0,59 | 26,11 |
| 3 | 5,12 | 1119 | 17,30 | 68,70 | 4,52 | 1,02 | 0,07 | 0,13 | 0,58 | 6,33 | 5,75 | 6,25 | - | 0,83 | 1,43 | - | 33,77 |
| 4 | 5,14 | 2254 | 1,90 | 21,80 | 0,75 | 0,58 | 0,00 | 0,03 | 0,17 | 1,53 | 1,36 | 1,42 | - | 0,06 | 0,10 | - | 16,80 |
| 5 | 5,23 | 957 | 32,30 | 65,40 | 2,02 | 0,24 | 0,07 | 0,11 | 0,50 | 2,93 | 2,43 | 2,20 | - | 0,48 | 0,82 | 0,31 | 11,18 |
| 6 | 3,91 | 1804 | 21,40 | 44,80 | 0,56 | 0,60 | 0,04 | 0,09 | 1,72 | 3,01 | 2,00 | 1,16 | 0,71 | 1,04 | 1,78 | 3,94 | 8,66 |
| 7 | 3,90 | 3705 | 8,30 | 63,40 | 0,41 | 0,62 | 0,01 | 0,13 | 2,45 | 3,62 | 2,66 | 2,10 | 1,49 | 0,79 | 1,36 | 7,13 | 7,13 |
| 8 | 3,86 | 3906 | 1,50 | 59,30 | 0,31 | 1,34 | 0,14 | 0,14 | 2,05 | 3,97 | 3,33 | 2,03 | 1,41 | 0,40 | 0,69 | 6,41 | 5,68 |
| 9 | 3,87 | 4655 | 0,00 | 48,90 | 0,00 | 2,23 | 0,02 | 0,10 | 1,32 | 3,67 | 3,46 | 2,29 | 1,11 | 0,08 | 0,13 | 3,94 | 13,01 |
| 10 | 4,38 | 2434 | 60,80 | 23,40 | 0,35 | 0,16 | 0,00 | 0,01 | 0,50 | 1,02 | 0,62 | 0,57 | 0,10 | 0,43 | 0,73 | 1,51 | 23,55 |
| 11 | 4,08 | 4590 | 92,00 | 17,50 | 0,17 | 0,21 | 0,06 | 0,00 | 0,46 | 0,90 | 0,57 | 0,40 | 0,13 | 0,25 | 0,43 | 1,48 | 16,60 |
| 12 | 4,60 | 4601 | 3,40 | 13,80 | 0,03 | 0,00 | 0,04 | 0,00 | 0,14 | 0,21 | 0,11 | 0,18 | 0,04 | 0,05 | 0,09 | 0,37 | 15,00 |
| 13 | 4,40 | 1076 | 1,50 | 44,50 | 1,13 | 3,74 | 0,44 | 0,10 | 0,63 | 6,05 | 5,46 | 4,23 | 0,04 | 0,17 | 0,29 | 0,60 | 15,07 |
| 14 | 6,14 | 555 | 51,80 | 81,70 | 3,82 | 2,56 | 0,15 | 0,21 | - | 6,73 | 6,73 | 4,23 | - | 0,68 | 1,17 | - | 24,09 |
| 15 | 5,78 | 935 | 45,80 | 50,10 | 2,72 | 2,90 | 0,18 | 0,09 | - | 5,89 | 5,89 | 4,84 | - | 0,43 | 0,73 | - | 23,54 |
| 16 | 5,97 | 776 | 3,00 | 21,60 | 2,70 | 3,16 | 0,54 | 0,09 | - | 6,49 | 6,49 | 3,23 | - | 0,19 | 0,32 | - | 17,35 |
| 17 | 5,35 | 1687 | 65,30 | 48,00 | 2,67 | 0,50 | 0,06 | 0,09 | 0,41 | 3,74 | 3,33 | 3,66 | - | 0,51 | 0,88 | - | 24,97 |
| 18 | 5,27 | 1914 | 9,00 | 37,20 | 1,45 | 0,95 | 0,09 | 0,05 | 0,36 | 2,90 | 2,54 | 3,05 | - | 0,21 | 0,37 | - | 26,48 |
| 19 | 5,57 | 4181 | 49,50 | 17,90 | 0,89 | 1,32 | 0,02 | 0,02 | 0,34 | 2,60 | 2,26 | 1,33 | - | 0,25 | 0,43 | - | 22,97 |
| 20 | 4,65 | 8714 | 3,40 | 5,10 | 0,05 | 0,00 | 0,00 | 0,00 | 0,17 | 0,22 | 0,11 | 0,17 | 0,06 | 0,04 | 0,07 | 0,53 | 14,53 |
| 21 | 5,13 | 1702 | 23,30 | 248,50 | 2,66 | 1,01 | 0,07 | 0,66 | 0,67 | 5,07 | 4,40 | 3,69 | - | 0,90 | 1,54 | 0,70 | 13,87 |
| 22 | 5,37 | 1864 | 4,50 | 224,30 | 2,74 | 1,12 | 0,06 | 0,50 | 0,58 | 5,00 | 4,42 | 3,43 | - | 0,56 | 0,96 | 0,43 | 9,64 |
| 23 | 5,61 | 2351 | 2,60 | 148,70 | 1,85 | 1,01 | 0,12 | 0,31 | 0,40 | 3,69 | 3,29 | 3,89 | - | 0,28 | 0,48 | - | 11,21 |
| 24 | 4,50 | 2499 | 27,00 | 155,20 | 1,20 | 0,87 | 0,00 | 0,40 | 1,06 | 3,54 | 2,59 | 3,00 | 0,11 | 0,66 | 1,14 | 3,07 | 13,99 |
| 25 | 4,51 | 2448 | 3,80 | 113,30 | 1,28 | 0,94 | 0,04 | 0,28 | 1,05 | 3,59 | 2,70 | 2,56 | 0,16 | 0,33 | 0,57 | 3,03 | 7,25 |
| 26 | 4,22 | 3265 | 1,90 | 65,70 | 1,11 | 0,94 | 0,06 | 0,18 | 0,93 | 3,22 | 2,47 | 2,40 | 0,18 | 0,19 | 0,32 | 2,14 | 8,19 |
| 27 | 4,24 | 3097 | 1,10 | 47,40 | 0,97 | 1,07 | 0,05 | 0,10 | 1,05 | 3,25 | 2,57 | 2,53 | 0,37 | 0,14 | 0,24 | 2,81 | 8,41 |
| 28 | 4,65 | 2602 | 19,90 | 137,80 | 1,67 | 0,54 | 0,00 | 0,31 | 1,01 | 3,54 | 2,62 | 1,76 | 0,09 | 0,69 | 1,19 | 2,39 | 7,46 |
| 29 | 4,33 | 3339 | 2,30 | 65,60 | 1,00 | 1,29 | 0,04 | 0,17 | 1,27 | 3,78 | 2,90 | 2,57 | 0,39 | 0,27 | 0,47 | 3,06 | 7,05 |
| 30 | 4,25 | 3436 | 1,10 | 52,10 | 0,81 | 1,57 | 0,02 | 0,10 | 1,08 | 3,58 | 2,83 | 2,18 | 0,33 | 0,16 | 0,28 | 3,03 | 6,05 |

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Table 4.2. Continued.

| Sample no. | pH (1 M KCl) | Electrical resistance (ohms) | Bray2 P (mg $kg^{-1}$) | Bray2 K (mg $kg^{-1}$) | Extractable cations (cmol(+) $kg^{-1}$ soil) Ca | Mg | Na | K | H | T-values (cmol(+) $kg^{-1}$ soil) TH | TAl | CEC (cmol(+) $kg^{-1}$ soil) | Al (cmol(+) $kg^{-1}$ soil) | Org. C (%) | Org. mat. (%) | Lime requirement (t $ha^{-1}$) | $CEC_{clay}$ (cmol(+) $kg^{-1}$ clay) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 31 | 4,39 | 2541 | 52,50 | 113,60 | 1,12 | 0,92 | 0,06 | 0,30 | 1,12 | 3,51 | 2,66 | 2,51 | 0,27 | 0,56 | 0,96 | 2,80 | 12,18 |
| 32 | 4,13 | 3186 | 4,90 | 66,20 | 0,83 | 1,11 | 0,11 | 0,24 | 1,57 | 3,84 | 3,10 | 2,92 | 0,83 | 0,27 | 0,47 | 4,78 | 8,98 |
| 33 | 4,01 | 2713 | 1,90 | 42,00 | 0,58 | 2,19 | 0,00 | 0,13 | 1,81 | 4,70 | 4,46 | 3,48 | 1,57 | 0,14 | 0,24 | 5,41 | 10,12 |
| 34 | 4,39 | 2300 | 72,40 | 65,90 | 1,02 | 0,84 | 0,03 | 0,16 | 1,03 | 3,08 | 2,17 | 1,88 | 0,12 | 0,89 | 1,52 | 2,99 | 18,47 |
| 35 | 4,42 | 5055 | 12,40 | 36,40 | 0,65 | 0,61 | 0,10 | 0,06 | 0,66 | 2,08 | 1,55 | 1,27 | 0,13 | 0,30 | 0,52 | 2,00 | 12,41 |
| 36 | 4,45 | 2189 | 56,10 | 127,90 | 1,37 | 0,91 | 0,11 | 0,32 | 0,51 | 3,22 | 2,93 | 2,27 | 0,22 | 1,03 | 1,76 | 11,47 | |
| 37 | 4,23 | 3895 | 6,00 | 72,40 | 0,65 | 0,87 | 0,06 | 0,18 | 1,97 | 3,73 | 2,53 | 2,12 | 0,77 | 0,56 | 0,97 | 6,69 | 6,90 |
| 38 | 4,25 | 5542 | 1,50 | 68,20 | 0,40 | 0,94 | 0,33 | 0,18 | 1,53 | 3,38 | 2,32 | 1,74 | 0,47 | 0,30 | 0,52 | 5,19 | 5,85 |
| 39 | 4,63 | 3098 | 0,75 | 23,60 | 0,38 | 0,90 | 0,04 | 0,03 | 0,88 | 2,23 | 1,46 | 1,68 | 0,11 | 0,16 | 0,27 | 2,74 | 5,61 |
| 40 | 4,62 | 951 | 1,10 | 228,20 | 0,69 | 1,02 | 0,08 | 0,67 | 1,08 | 3,54 | 2,60 | 2,53 | 0,14 | 0,43 | 0,73 | 1,76 | 6,72 |
| 41 | 6,70 | 454 | 16,90 | 132,20 | 3,37 | 3,55 | 0,21 | 0,25 | - | 7,37 | 7,37 | 6,83 | - | 0,82 | 1,41 | - | 46,88 |
| 42 | 5,18 | 3738 | 28,10 | 44,40 | 0,93 | 0,93 | 0,01 | 0,08 | 0,50 | 2,45 | 1,95 | 1,56 | - | 0,34 | 0,58 | 0,24 | 26,09 |
| 43 | 4,23 | 2782 | 3,40 | 30,40 | 0,18 | 0,30 | 0,00 | 0,03 | 0,52 | 1,02 | 0,73 | 0,60 | 0,23 | 0,07 | 0,13 | 1,68 | 11,05 |
| 44 | 4,31 | 4553 | 1,90 | 85,00 | 0,41 | 1,44 | 0,09 | 0,23 | 1,06 | 3,23 | 2,46 | 1,89 | 0,29 | 0,20 | 0,34 | 3,39 | 6,37 |
| 45 | 5,15 | 1244 | 42,80 | 13,40 | 0,48 | 0,35 | 0,05 | 0,00 | 0,31 | 1,20 | 0,89 | 1,13 | - | 0,21 | 0,35 | 0,52 | 46,69 |
| 46 | 4,52 | 2033 | 25,10 | 18,20 | 0,23 | 0,58 | 0,04 | 0,01 | 0,51 | 1,37 | 1,00 | 0,62 | 0,14 | 0,32 | 0,55 | 1,35 | 13,75 |
| 47 | 6,05 | 1280 | 57,40 | 54,40 | 1,88 | 1,19 | 0,03 | 0,10 | - | 3,19 | 3,19 | 1,84 | - | 0,35 | 0,60 | - | 16,24 |
| 48 | 4,23 | 3875 | 0,00 | 9,20 | 0,12 | 1,41 | 0,49 | 0,01 | 1,06 | 3,09 | 2,74 | 1,61 | 0,71 | 0,20 | 0,34 | 3,58 | 5,74 |
| 49 | 7,85 | 547 | 255,00 | 608,00 | 6,89 | 3,36 | 0,28 | 1,22 | - | 11,76 | 11,76 | 5,78 | - | 0,79 | 1,35 | - | 29,55 |
| 50 | 7,71 | 166 | 202,50 | 208,70 | 9,77 | 3,54 | 1,16 | 0,53 | - | 15,01 | 15,01 | 7,33 | - | 0,59 | 1,02 | - | 23,17 |
| 51 | 7,69 | 576 | 202,50 | 388,60 | 3,82 | 3,22 | 0,26 | 0,83 | - | 8,12 | 8,12 | 6,39 | - | 0,78 | 1,35 | - | 47,62 |
| 52 | 7,46 | 500 | 187,50 | 331,80 | 5,19 | 3,13 | 0,49 | 0,69 | - | 9,50 | 9,50 | 7,59 | - | 0,67 | 1,15 | - | 27,26 |
| 53 | 4,53 | 2405 | 6,75 | 43,90 | 0,63 | 0,44 | 0,05 | 0,08 | 0,89 | 2,08 | 1,43 | 1,23 | 0,24 | 0,28 | 0,48 | 2,79 | 9,67 |
| 54 | 4,80 | 1930 | 137,30 | 68,40 | 1,07 | 0,64 | 0,06 | 0,12 | 0,95 | 2,84 | 2,01 | 1,87 | 0,12 | 0,70 | 1,21 | 2,59 | 11,48 |
| 55 | 4,60 | 2842 | 66,40 | 12,10 | 0,49 | 0,95 | 0,02 | 0,04 | 0,58 | 2,08 | 1,65 | 0,97 | 0,15 | 0,37 | 0,64 | 1,71 | 12,58 |
| 56 | 7,08 | 867 | 47,60 | 189,80 | 8,79 | 4,01 | 0,21 | 0,51 | - | 13,53 | 13,53 | 9,59 | - | 0,74 | 1,27 | - | 75,45 |
| 57 | 7,01 | 580 | 27,40 | 44,30 | 6,59 | 4,09 | 0,30 | 0,11 | - | 11,10 | 11,10 | 9,13 | - | 0,40 | 0,69 | - | 91,57 |
| 58 | 6,91 | 519 | 35,60 | 53,60 | 5,04 | 3,93 | 0,41 | 0,10 | - | 9,48 | 9,48 | 9,82 | - | 0,36 | 0,62 | - | 84,62 |
| 59 | 4,19 | 2107 | 123,80 | 68,10 | 1,18 | 0,59 | 0,06 | 0,17 | 2,19 | 4,19 | 2,85 | 2,45 | 0,85 | 1,25 | 2,14 | 6,76 | 13,79 |
| 60 | 4,34 | 3724 | 87,80 | 67,70 | 0,52 | 0,69 | 0,49 | 0,14 | 1,22 | 3,06 | 2,19 | 1,47 | 0,35 | 0,62 | 1,07 | 4,06 | 12,50 |

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Table 4.2. Continued.

| Sample no. | pH (1 M KCl) | Electrical resis-tance (ohms) | Bray2 P (mg $kg^{-1}$) | Bray2 K (mg $kg^{-1}$) | Extractable cations (cmol(+) $kg^{-1}$ soil) Ca | Mg | Na | K | H | T-values (cmol(+) $kg^{-1}$ soil) TH | TAl | CEC (cmol(+) $kg^{-1}$ soil) | Al (cmol(+) $kg^{-1}$ soil) | Org. C (%) | Org. mat. (%) | Lime requirement (t $ha^{-1}$) | $CEC_{clay}$ (cmol(+) $kg^{-1}$ clay) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 61 | 4,16 | 1797 | 54,80 | 28,90 | 0,39 | 0,55 | 0,16 | 0,06 | 1,46 | 2,61 | 1,78 | 1,24 | 0,63 | 0,51 | 0,88 | 5,00 | 9,44 |
| 62 | 5,37 | 6879 | 124,50 | 34,10 | 1,15 | 0,57 | 0,00 | 0,05 | 0,61 | 2,38 | 1,77 | 1,24 | - | 0,67 | 1,16 | 1,38 | 19,68 |
| 63 | 5,27 | 8070 | 38,60 | 25,60 | 0,52 | 0,60 | 0,03 | 0,01 | 0,32 | 1,47 | 1,15 | 0,93 | - | 0,17 | 0,29 | 0,77 | 17,00 |
| 64 | 6,13 | 1167 | 66,00 | 117,40 | 2,05 | 1,86 | 0,19 | 0,22 | - | 4,32 | 4,32 | 2,86 | - | 0,21 | 0,36 | - | 42,69 |
| 65 | 4,93 | 2262 | 296,30 | 83,70 | 4,81 | 2,59 | 0,01 | 0,19 | 1,49 | 9,09 | 7,66 | 4,08 | 0,06 | 2,11 | 3,63 | 2,03 | 25,86 |
| 66 | 5,90 | 1956 | 92,30 | 81,10 | 1,40 | 0,98 | 0,10 | 0,17 | - | 2,65 | 2,65 | 1,63 | - | 0,27 | 0,47 | - | 31,71 |
| 67 | 5,67 | 573 | 161,30 | 202,20 | 2,74 | 2,45 | 0,13 | 0,50 | - | 5,82 | 5,82 | 5,91 | - | 1,11 | 1,91 | - | 20,02 |
| 68 | 3,97 | 668 | 206,30 | 70,70 | 0,50 | 0,45 | 0,03 | 0,19 | 1,21 | 2,37 | 1,63 | 0,88 | 0,47 | 0,52 | 0,89 | 3,95 | 16,76 |
| 69 | 4,74 | 4267 | 153,80 | 32,20 | 0,57 | 0,51 | 0,09 | 0,09 | 0,62 | 1,87 | 1,34 | 1,70 | 0,09 | 0,42 | 0,72 | 1,84 | 37,36 |
| 70 | 5,44 | 1634 | 105,00 | 69,90 | 1,62 | 0,53 | 0,00 | 0,14 | 0,34 | 2,63 | 2,29 | 1,03 | - | 0,40 | 0,69 | - | 12,13 |
| 71 | 4,38 | 1974 | 31,88 | 80,85 | 0,96 | 1,17 | 0,07 | 0,23 | 0,97 | 3,40 | 2,61 | 1,98 | 0,18 | 0,58 | 0,99 | 2,95 | 9,33 |

*For explanation of symbols and abbreviations please refer to p. 4.5 and 4.6 in text (Chapter 4).

Table 4.3. Selected physical soil properties* of the soils sampled for compaction studies.

| | Maximum compaction | | | MOR (kPa) | | Total porosity (%) | | |
|---|---|---|---|---|---|---|---|---|
| Sample no. | Water content (g 100 $g^{-1}$) | Max.BD (Mg $m^{-3}$) | Field BD (Mg $m^{-3}$) | MOR1 (1 Hour) | MOR2 (12 Hours) | at Max. BD | at Field BD | Relative compaction in field (%) |
| 1 | 15,50 | 1,68 | 1,607 | 5,89 | 78,00 | 37,08 | 39,68 | 95,87 |
| 2 | 11,25 | 1,79 | 1,646 | 4,00 | 39,35 | 31,91 | 37,50 | 91,79 |
| 3 | 13,75 | 1,77 | 1,642 | 88,89 | 398,46 | 32,19 | 36,98 | 92,94 |
| 4 | 8,50 | 1,98 | 1,947 | 18,23 | 204,48 | 25,47 | 26,52 | 98,58 |
| 5 | 10,90 | 2,03 | 1,820 | 10,83 | 239,99 | 24,27 | 31,92 | 89,90 |
| 6 | 8,75 | 2,03 | 1,541 | 31,98 | 100,85 | 21,97 | 40,87 | 75,78 |
| 7 | 11,13 | 1,95 | 1,743 | 15,01 | 191,29 | 25,56 | 33,37 | 89,52 |
| 8 | 16,00 | 1,81 | 1,764 | 10,56 | 94,39 | 32,09 | 33,74 | 97,57 |
| 9 | 15,35 | 1,77 | 1,677 | 17,31 | 74,26 | 33,39 | 36,88 | 94,77 |
| 10 | 13,00 | 1,88 | 1,680 | 3,84 | 12,14 | 28,87 | 36,37 | 89,46 |
| 11 | 11,00 | 1,93 | 1,766 | 2,67 | 12,44 | 26,86 | 33,01 | 91,59 |
| 12 | 4,63 | 1,78 | 1,729 | 5,60 | 21,12 | 32,91 | 34,65 | 97,41 |
| 13 | 12,50 | 1,90 | 2,042 | 78,06 | 171,53 | 28,66 | 23,13 | 107,76 |
| 14 | 11,90 | 1,89 | 1,480 | 110,64 | 239,16 | 26,97 | 42,92 | 78,15 |
| 15 | 12,25 | 1,92 | 1,675 | 147,63 | 463,88 | 26,68 | 35,92 | 87,40 |
| 16 | 10,25 | 1,99 | 1,868 | 136,40 | 347,66 | 24,43 | 29,12 | 93,79 |
| 17 | 9,75 | 1,94 | 1,615 | 54,75 | 236,19 | 24,64 | 37,39 | 83,09 |
| 18 | 7,63 | 2,08 | 1,766 | 84,89 | 279,90 | 20,28 | 32,31 | 84,90 |
| 19 | 8,00 | 1,90 | 1,597 | 7,88 | 112,20 | 28,00 | 39,58 | 83,92 |
| 20 | 4,32 | 1,84 | 1,716 | 2,85 | 4,27 | 30,33 | 35,01 | 93,27 |
| 21 | 12,30 | 1,88 | 1,710 | 16,26 | 268,07 | 28,94 | 35,41 | 90,90 |
| 22 | 16,50 | 1,80 | 1,554 | 11,10 | 237,68 | 32,82 | 41,84 | 86,57 |
| 23 | 14,50 | 1,83 | 1,513 | 5,26 | 199,58 | 31,96 | 43,68 | 82,77 |
| 24 | 11,25 | 1,95 | 1,696 | 10,43 | 92,62 | 26,50 | 36,07 | 86,97 |
| 25 | 13,50 | 1,84 | 1,572 | 5,19 | 139,82 | 31,11 | 41,14 | 85,44 |
| 26 | 10,25 | 2,01 | 1,653 | 11,09 | 89,92 | 24,94 | 38,16 | 82,39 |
| 27 | 11,00 | 1,96 | 1,685 | 7,11 | 156,29 | 26,77 | 36,92 | 86,15 |
| 28 | 10,25 | 1,98 | 1,742 | 10,19 | 225,15 | 25,42 | 34,22 | 88,20 |
| 29 | 11,50 | 1,93 | 1,748 | 6,96 | 107,63 | 27,81 | 34,62 | 90,57 |
| 30 | 12,75 | 1,88 | 1,715 | 6,27 | 163,86 | 29,95 | 35,93 | 91,47 |

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Table 4.3. Continued.

| Sample no. | Maximum compaction: Water content (g 100 $g^{-1}$) | Maximum compaction: Max. BD (Mg $m^{-3}$) | Field BD (Mg $m^{-3}$) | MOR (kPa): MOR1 (1 Hour) | MOR (kPa): MOR2 (12 Hours) | Total porosity (%): at Max. BD | Total porosity (%): at Field BD | Relative compaction in field (%) |
|---|---|---|---|---|---|---|---|---|
| 31 | 9,75 | 2,01 | 1,845 | 12,70 | 242,68 | 24,23 | 30,33 | 91,96 |
| 32 | 13,75 | 1,89 | 1,719 | 9,82 | 220,94 | 28,67 | 35,25 | 90,77 |
| 33 | 14,50 | 1,83 | 1,805 | 26,52 | 194,88 | 31,47 | 32,22 | 98,90 |
| 34 | 10,55 | 1,92 | 1,606 | 4,85 | 74,51 | 26,91 | 38,75 | 83,80 |
| 35 | 8,40 | 2,02 | 1,670 | 27,58 | 123,76 | 23,35 | 36,71 | 82,57 |
| 36 | 12,20 | 1,87 | 1,619 | 2,58 | 61,22 | 28,87 | 38,50 | 86,46 |
| 37 | 14,20 | 1,81 | 1,573 | 2,01 | 90,63 | 31,92 | 40,92 | 86,79 |
| 38 | 12,50 | 1,83 | 1,269 | 0,00 | 88,82 | 31,76 | 52,55 | 69,53 |
| 39 | 14,95 | 1,83 | 1,597 | 0,00 | 51,45 | 31,76 | 40,44 | 87,27 |
| 40 | 11,50 | 2,08 | - | 25,93 | 102,06 | 22,89 | - | - |
| 41 | 13,25 | 1,84 | 1,555 | 22,61 | 224,50 | 31,28 | 41,86 | 84,60 |
| 42 | 8,60 | 1,99 | 1,614 | 8,66 | 53,40 | 24,57 | 38,76 | 81,20 |
| 43 | 7,13 | 2,03 | 1,687 | 9,45 | 46,30 | 23,23 | 36,31 | 82,97 |
| 44 | 13,0 | 1,82 | 1,370 | 3,48 | 83,92 | 31,63 | 48,43 | 75,44 |
| 45 | 8,00 | 1,76 | 1,617 | 2,74 | 14,18 | 33,36 | 38,85 | 91,77 |
| 46 | 7,50 | 1,81 | 1,711 | 0,00 | 12,52 | 30,98 | 34,89 | 94,34 |
| 47 | 8,25 | 2,05 | 1,860 | 12,33 | 18,05 | 22,14 | 29,35 | 90,73 |
| 48 | 15,50 | 1,60 | - | 14,58 | 123,92 | 39,09 | - | - |
| 49 | 14,75 | 1,80 | 1,387 | 45,58 | 218,58 | 32,92 | 48,31 | 77,06 |
| 50 | 18,50 | 1,78 | 1,472 | 101,48 | 363,40 | 34,61 | 45,77 | 82,93 |
| 51 | 14,50 | 1,79 | 1,328 | 19,32 | 150,07 | 33,54 | 50,56 | 74,40 |
| 52 | 16,00 | 1,79 | 1,444 | 110,11 | 355,67 | 33,84 | 46,48 | 80,90 |
| 53 | 9,90 | 2,00 | 1,702 | 4,32 | 92,83 | 24,54 | 35,79 | 85,10 |
| 54 | 10,00 | 1,94 | 1,625 | 4,44 | 26,26 | 26,29 | 38,26 | 83,76 |
| 55 | 8,00 | 1,98 | 1,716 | 10,89 | 47,61 | 24,95 | 34,79 | 86,89 |
| 56 | 15,50 | 1,72 | 1,459 | 14,53 | 121,27 | 35,69 | 45,42 | 84,88 |
| 57 | 14,00 | 1,69 | 1,467 | 7,30 | 158,82 | 37,19 | 45,40 | 86,93 |
| 58 | 15,25 | 1,82 | 1,550 | 15,95 | 266,78 | 32,83 | 42,68 | 85,32 |
| 59 | 12,25 | 1,88 | 1,724 | 13,13 | 94,84 | 29,03 | 34,95 | 91,65 |
| 60 | 11,50 | 1,79 | 1,551 | 3,56 | 36,61 | 32,51 | 41,52 | 86,68 |

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Table 4.3. Continued.

| Sample no. | Maximum compaction: Water content (g 100 g$^{-1}$) | Maximum compaction: Max. BD (Mg m$^{-3}$) | Field BD (Mg m$^{-3}$) | MOR (kPa): MOR1 (1 Hour) | MOR (kPa): MOR2 (12 Hours) | Total porosity (%): at Max. BD | Total porosity (%): at Field BD | Relative compaction in field (%) |
|---|---|---|---|---|---|---|---|---|
| 61 | 12,00 | 1,84 | 1,741 | 7,92 | 69,33 | 30,91 | 34,47 | 94,84 |
| 62 | 9,00 | 1,96 | 1,783 | 0,00 | 8,09 | 25,59 | 32,24 | 91,06 |
| 63 | 7,50 | 2,01 | 1,855 | 13,14 | 57,32 | 24,20 | 29,87 | 92,52 |
| 64 | 10,00 | 1,82 | 1,581 | 10,98 | 94,97 | 32,06 | 40,99 | 86,87 |
| 65 | 16,50 | 1,68 | 1,329 | 2,51 | 58,47 | 35,54 | 49,14 | 78,90 |
| 66 | 8,75 | 1,96 | 1,799 | 9,25 | 64,70 | 25,96 | 32,13 | 91,67 |
| 67 | 14,10 | 1,84 | 1,925 | 6,06 | 304,48 | 29,49 | 26,12 | 104,78 |
| 68 | 9,00 | 1,92 | 1,828 | 0,00 | 13,95 | 27,06 | 30,37 | 95,46 |
| 69 | 8,00 | 1,93 | 1,722 | 0,00 | 7,67 | 26,95 | 34,67 | 89,43 |
| 70 | 9,50 | 1,94 | - | 11,99 | 59,41 | 25,76 | - | - |
| 71 | 11,50 | 1,93 | 1,657 | 13,11 | 179,93 | 27,58 | 37,82 | 85,86 |

*For explanation of symbols and abbreviations please refer to p. 4.7 in text (Chapter 4).


**Plate 4.1** (Sample 2). This structureless loamy sand (Westleigh) recompacted to a relative compaction of 91,8% shortly after deep ploughing. A total of 78,9% of the particles of this poorly sorted soil was < 0,106 mm (Appendix 4). A gradual increase in PSS was measured.


**Plate 4.2** (Samples 6 and 7). On this coarse textured Glenrosa soil (47% gravel in A horizon and 27% in B21 horizon), the sharp transition from loose to compact soil at the working depth, prevented the grapevine roots from penetrating the subsoil, although the contact surface was not smeared.

**Plate 4.3** (Sample 8). The bottom of the plough share smeared the soil of this B22 horizon (clay loam) on the working depth at 900 mm in this granitic Glenrosa. The roots were removed to expose the smeared surface.

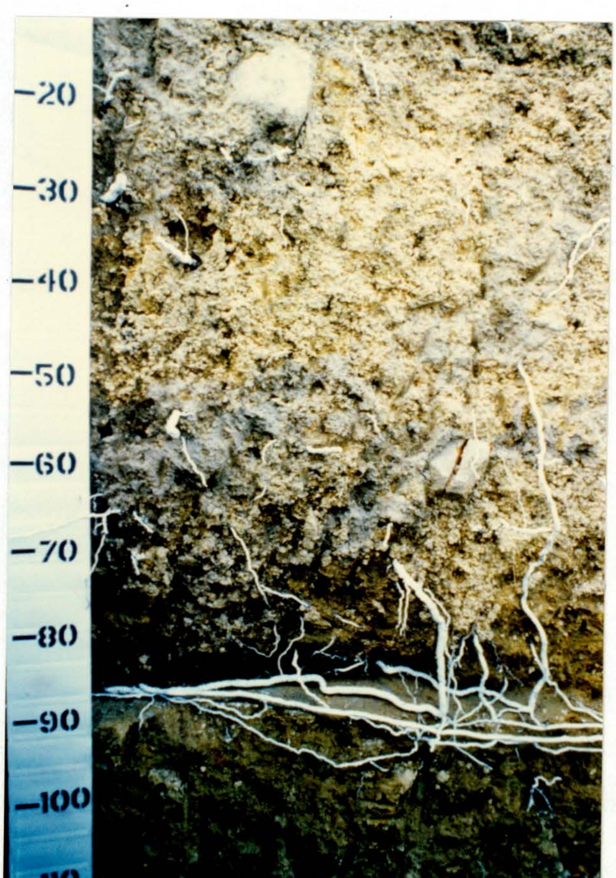


**Plate 4.4** (Sample 8). Root growth was abruptly impeded by the smeared surface at the working depth in the B22 horizon (clay loam).

**Plate 4.5** (Sample 41). Massive soil structure due to clay puddling upon wetting and drying of this loamy alluvial soil (Dundee). Water infiltration on such a soil is a serious problem due to the unstable structure of the topsoil. This soil had a sharp increase in the fine sand fraction and a relative sharp increase in total silt fraction (Appendix 4). This soil had a total fine sand fraction of 33,80% and a total silt fraction of 34,99% (Appendices 2 and 4).

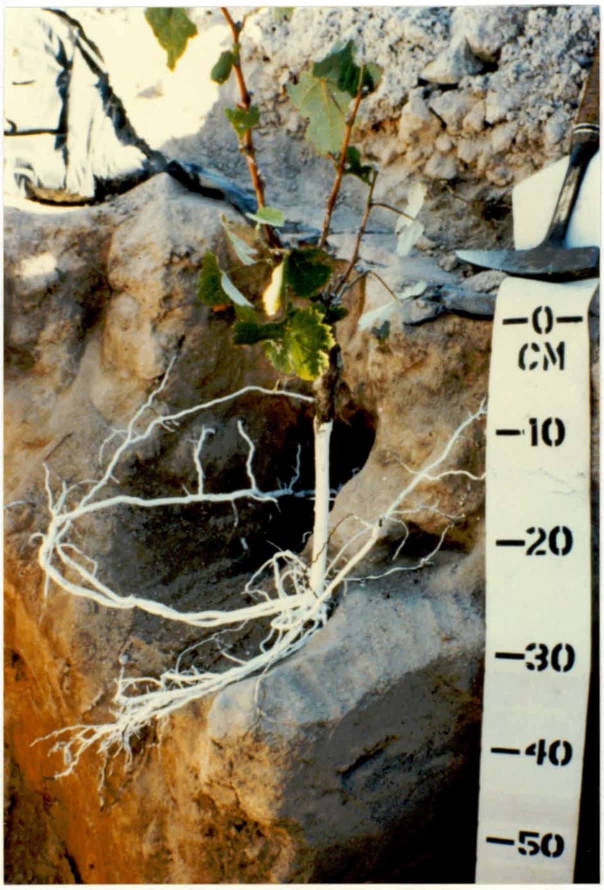


**Plate 4.6** (Sample 45). Roots were confined to the topsoil because they could not penetrate the subsoil (BD = 1,617 Mg $m^{-3}$) of this coarse sandy Longlands soil, which contained 25,3% coarse sand, 39,4% fine sand, and 6,7% silt + clay. Note the sharp increase in fine sand illustrated by the cumulative particle size distribution curve in Appendix 4. Roots were forced to grow upwards due to the limited rooting volume.

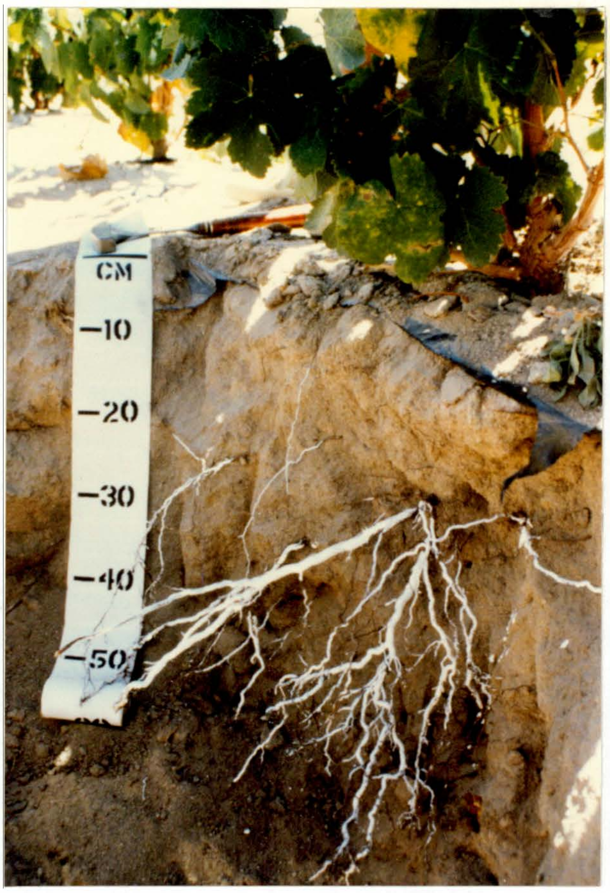


**Plate 4.7** (Sample 46). Well-developed root system on this soil in the same vineyard, and adjacent to the one in Plate 4.6, although this Longlands soil had a higher bulk density (1,711 Mg $m^{-3}$), as well as a higher relative compaction in the subsoil. This soil contained 42,5% coarse sand, 26,5% fine sand and 6,8% silt + clay, and the increase in fine sand on the cumulative particle size distribution curve in Appendix 4 was not so prominent. Note the angle of the penetrating roots.


**Plate 4.8** (Sample 47). Deep ploughing of this Avalon soil (sandy loam) when it was too wet caused considerable visual soil structural degradation, which, after only one growing season, already led to retarded growth.

**Plate 4.9** (Samples 49-52). Uneven growth is one of the first symptoms of compaction in vineyards, here shown for an alluvial soil (Oakleaf; sandy clay loam).

**Plate 4.10** (Samples 49-52). If not rectified in time, compaction can lead to the dying of grapevines, like on this Oakleaf soil (sandy clay loam). Note the absence of symptoms other than poor shoot growth.

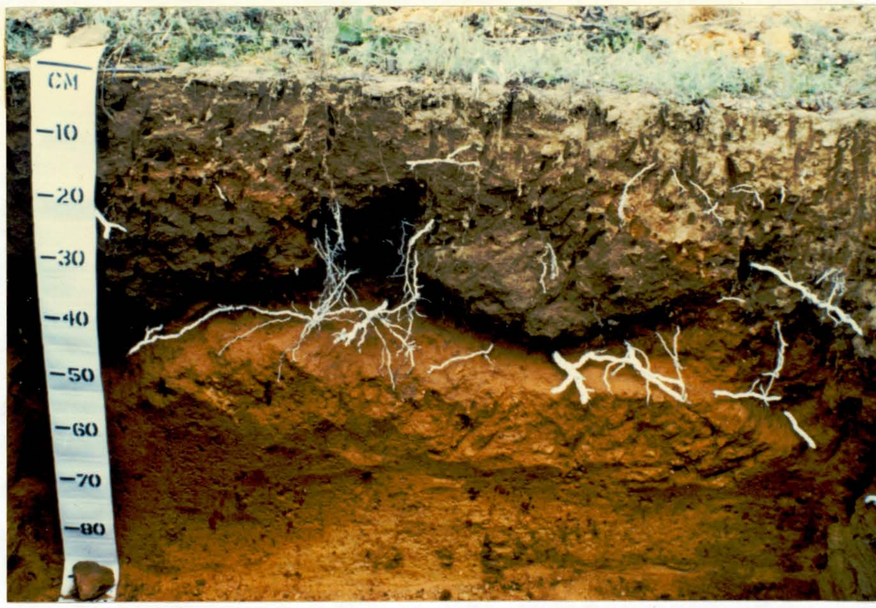


**Plate 4.11** (Samples 53 and 54). Shallow rooting due to shallow ploughing and natural subsoil compaction. Note the roots concentrated in the loose soil between the clods. When this soil is deep ploughed, it is regarded to be a high potential soil for growing grapevines.

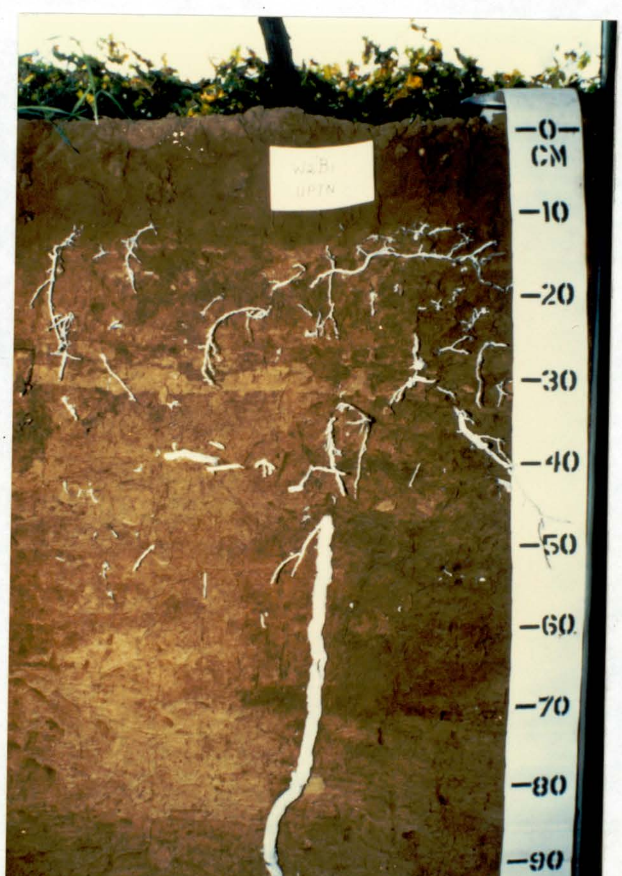


**Plate 4.12** (Samples 56-58). A subtle increase in fine sand content (Appendix 4) relative to the overlying layer (both layers were sandy loams) caused enough increase in PSS and bulk density to seriously impede root penetration deeper down in this Dundee soil at Upington.

**Plate 4.13** (Sample 63). The vineyard on this Pinedene soil had to be uprooted due to poor production because few roots could reach the loose subsoil due to a root restricting dense soil layer (40% coarse sand; 19,9% medium sand; 26,8 fine sand; 13% clay).


**Plate 4.14** (Sample 33). Although a "visible" compacted layer was not observed, very few roots penetrated deeper than 200 mm in this loamy sand (Longlands).

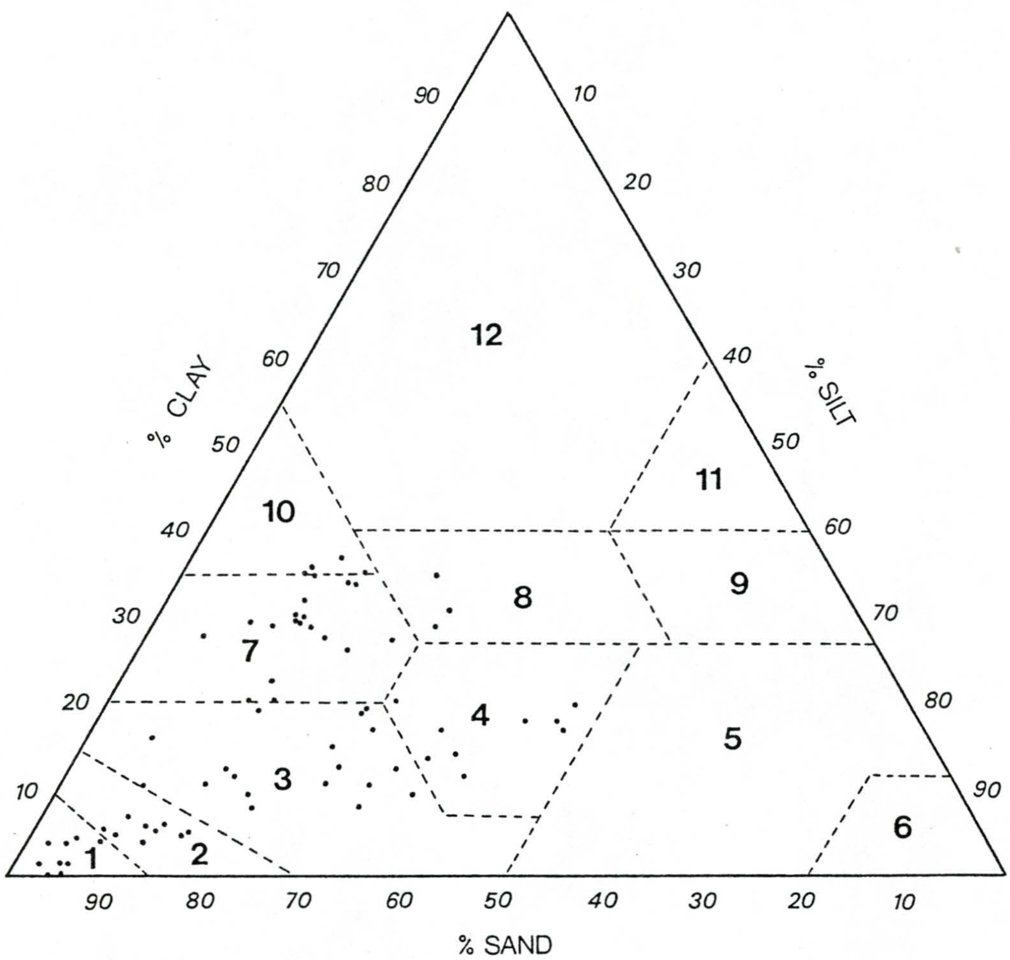


Fig. 4.1a. Soil texture triangle showing the textural spread (<2 mm ϕ basis) of the sample population. The broken lines demarcate the textural classes: (1) sand; (2) loamy sand; (3) sandy loam; (4) loam; (5) silt loam; (6) silt; (7) sandy clay loam; (8) clay loam; (9) silt clay loam; (10) sandy clay; (11) silty clay; and (12) clay.

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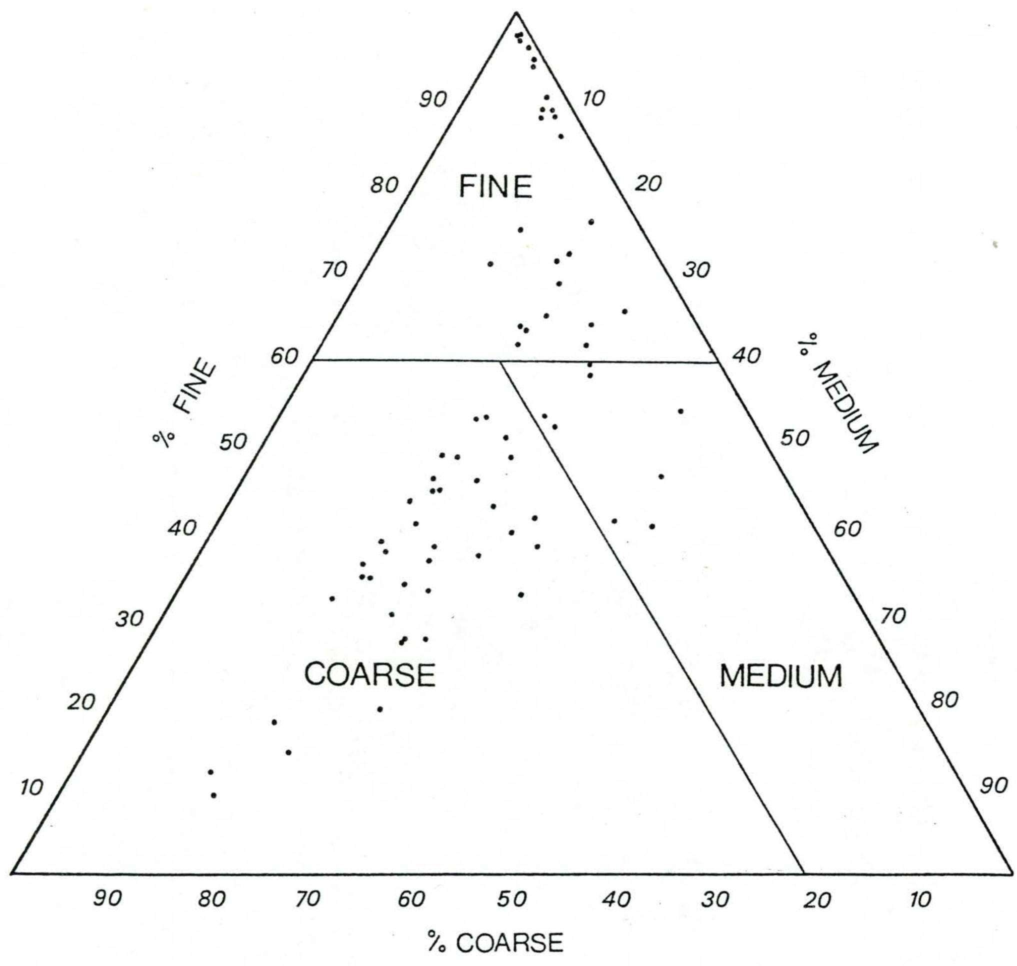
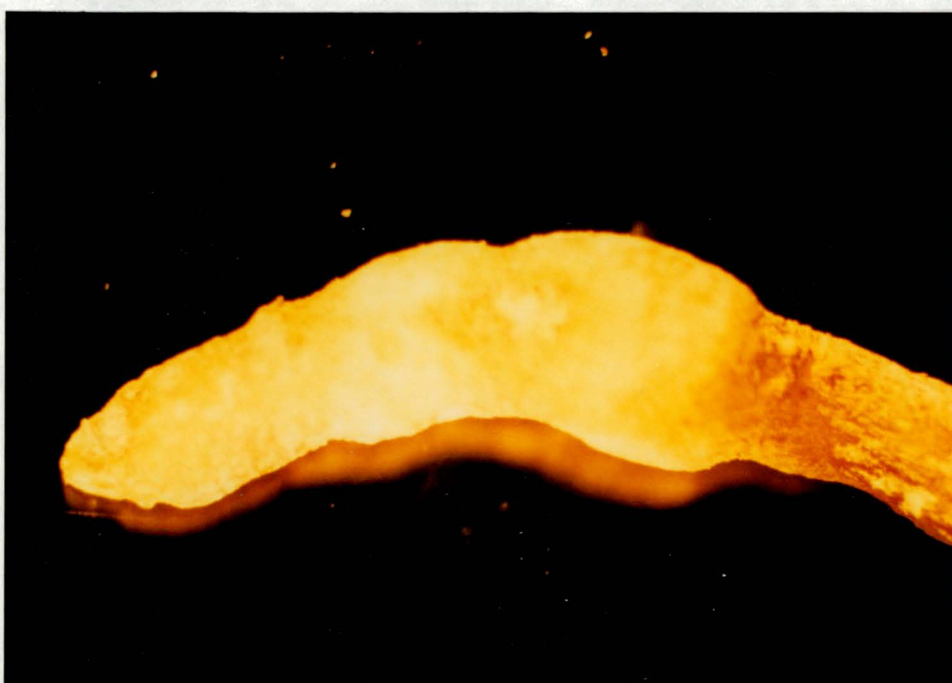



Fig. 4.1b. Sand grade chart showing the spread of the sand fraction of the sample population within the fine (0,05-0,25 mm), medium (0,25-0,50 mm) and coarse (0,50-2,00 mm) classes.

a



b

Fig. 4.2. Typical appearance of a healthy growing grapevine root tip: (a) Comparison of root tip with a pin; (b) Root tip is thinner a short distance back from the tip.

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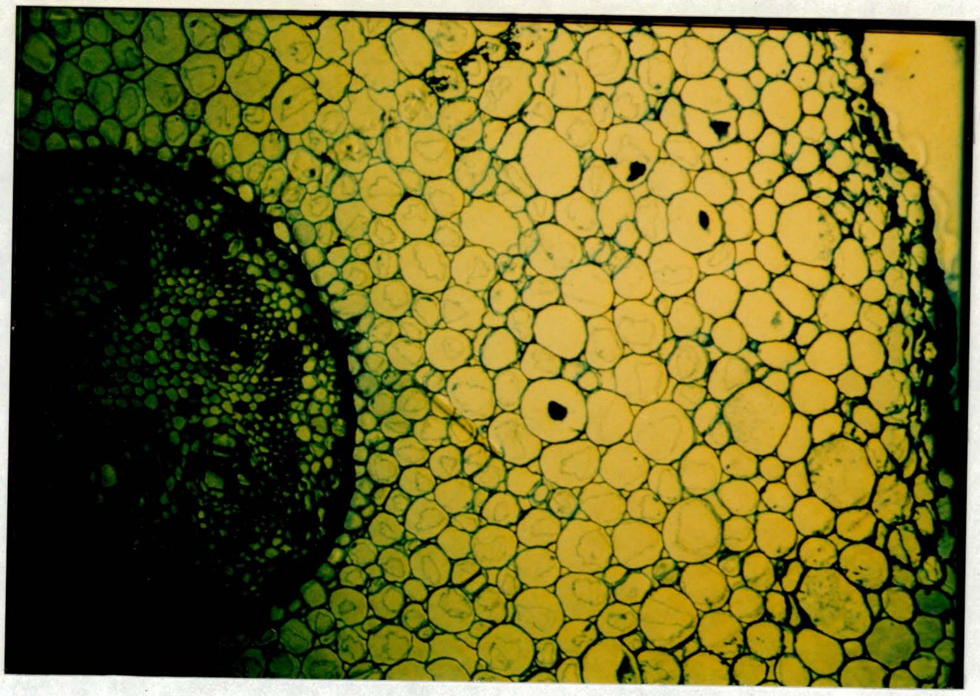

c

d

Fig. 4.2. Continued. Typical appearance of a healthy growing grapevine root tip: (c) Transverse section showing thick cortex layer; (d) Dead cortex tissue removed, demonstrating thinner root where secondary growth takes place.

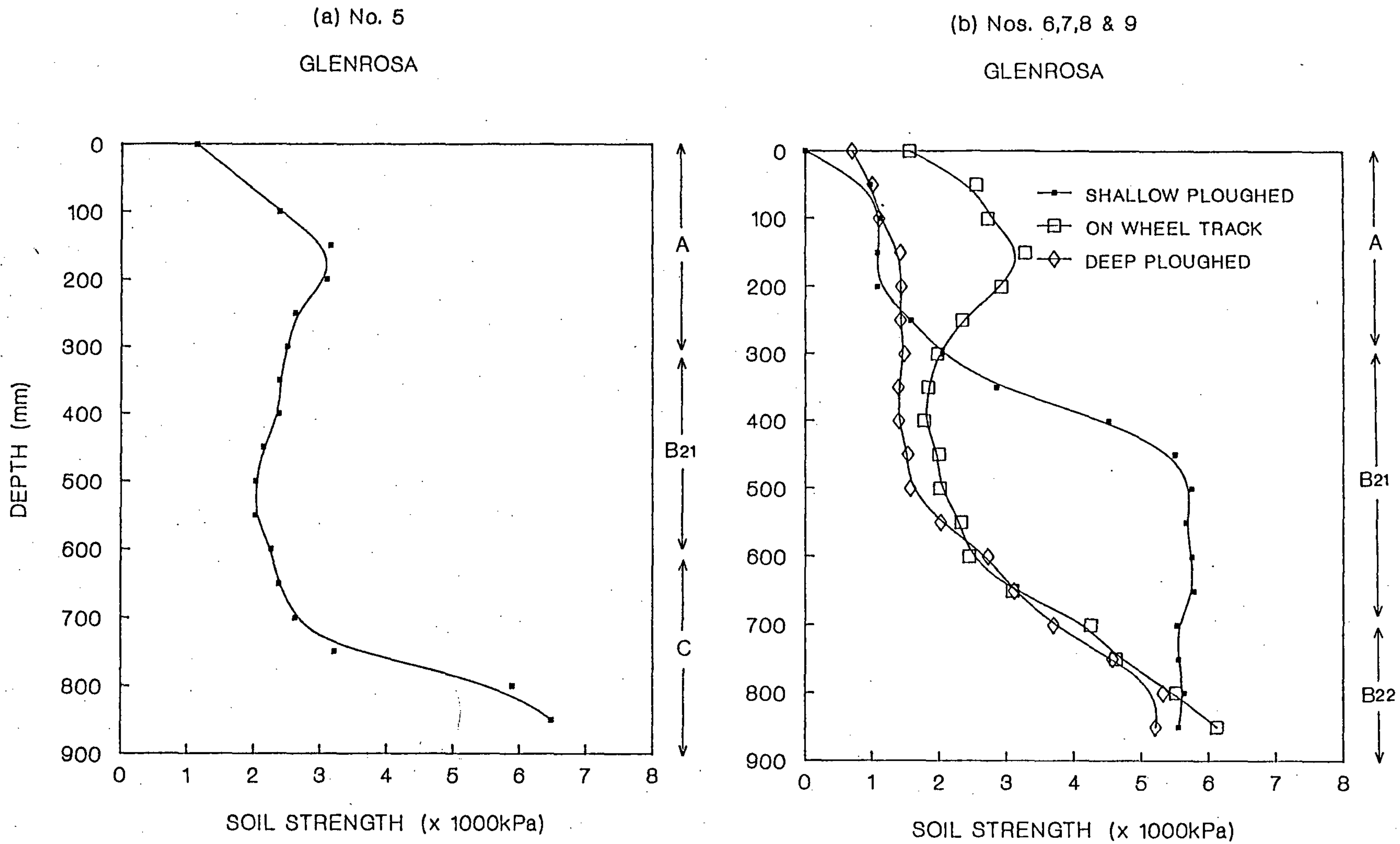


Fig. 4.3. Plot of penetrometer soil strength *versus* soil depth for selected soil profiles sampled for compaction studies (the numbers above the figures refer to the samples listed in Appendix 1, while the symbols on the Y2-axis indicate horizon depth).

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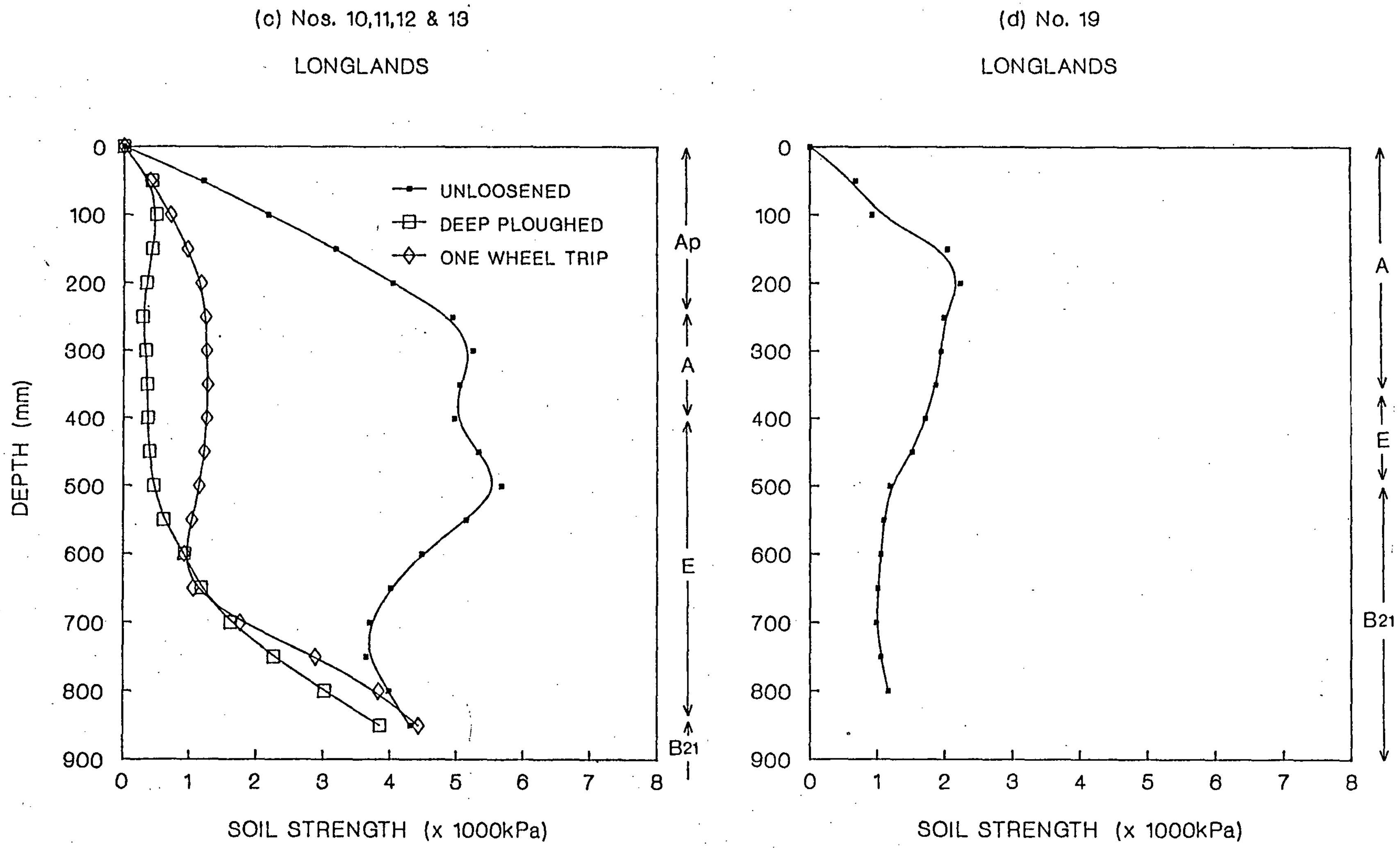


Fig. 4.3. Continued.

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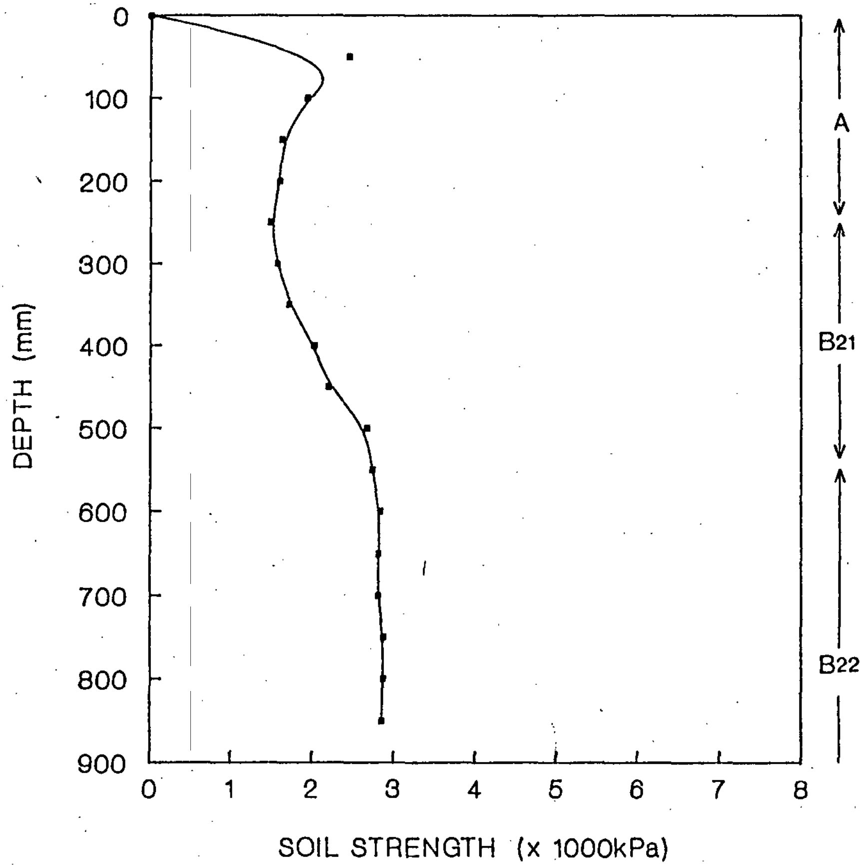
(e) Nos. 21,22 & 23

OAKLEAF




(f) Nos. 24,25,26 & 27

HUTTON

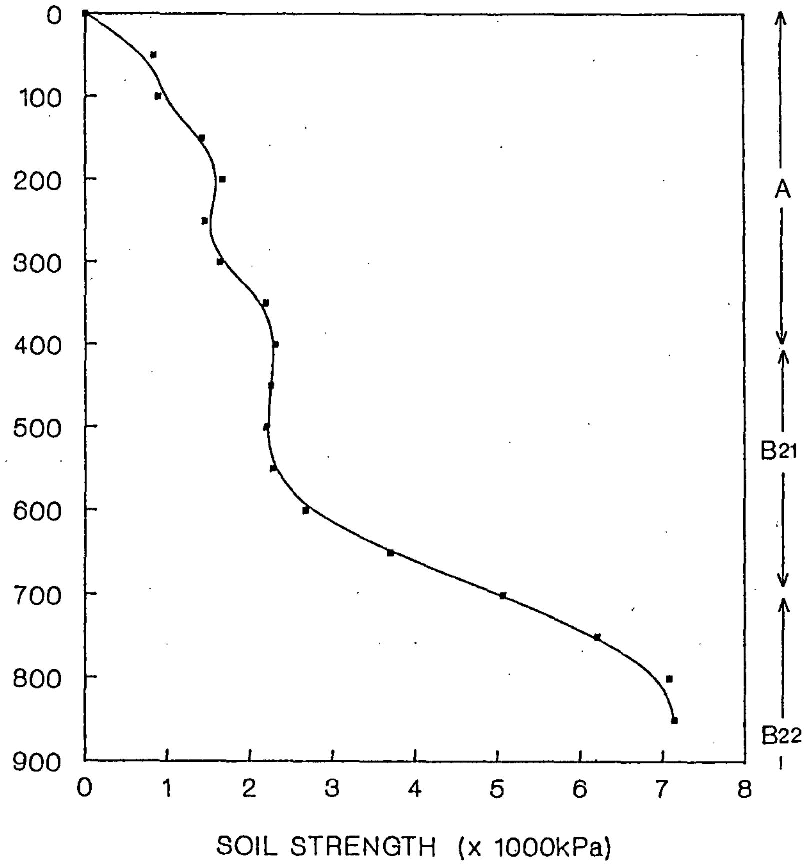



Fig. 4.3. Continued.

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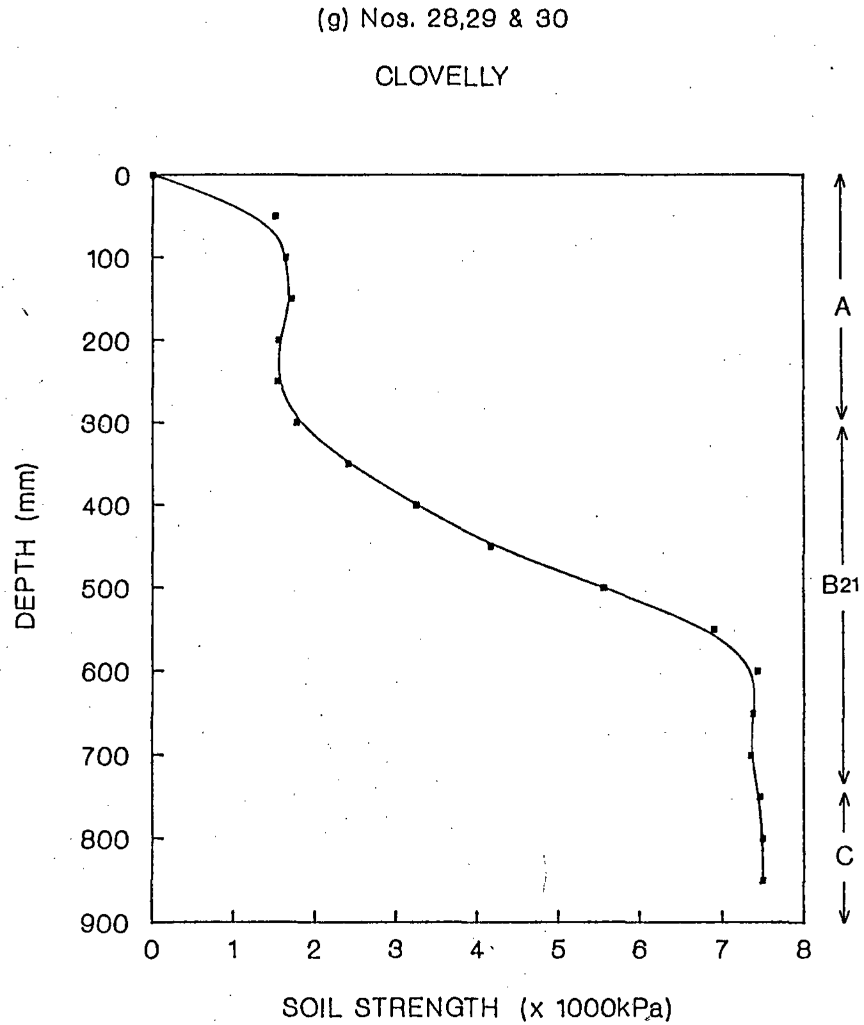


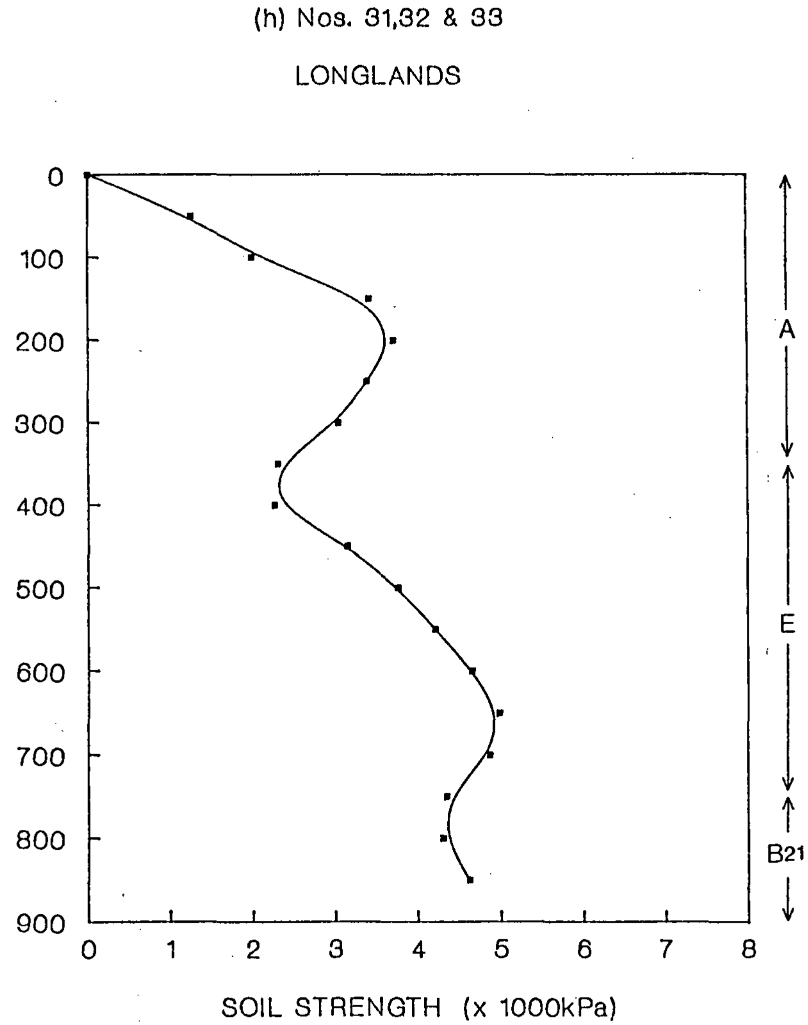


Fig. 4.3. Continued.

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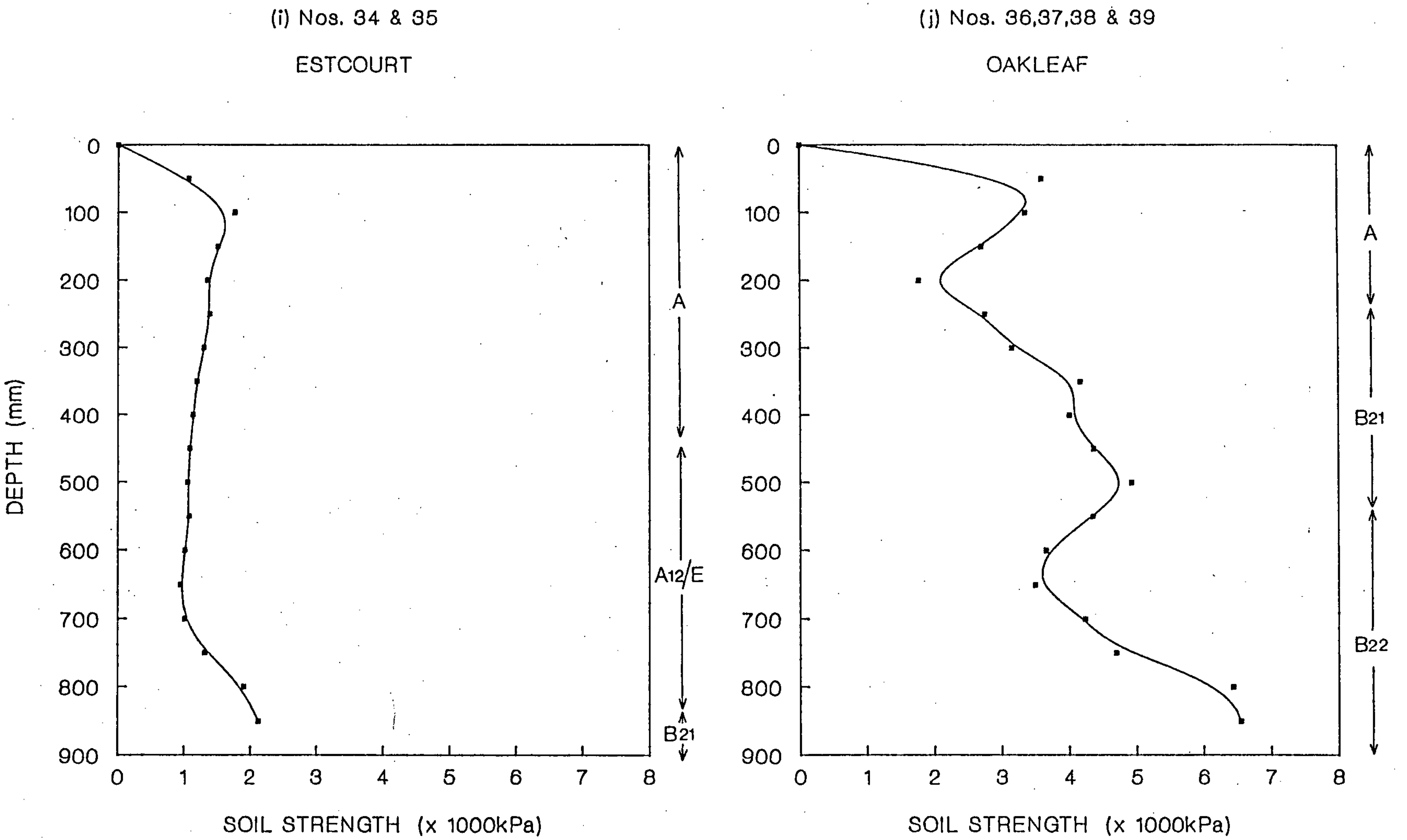


Fig. 4.3. Continued.

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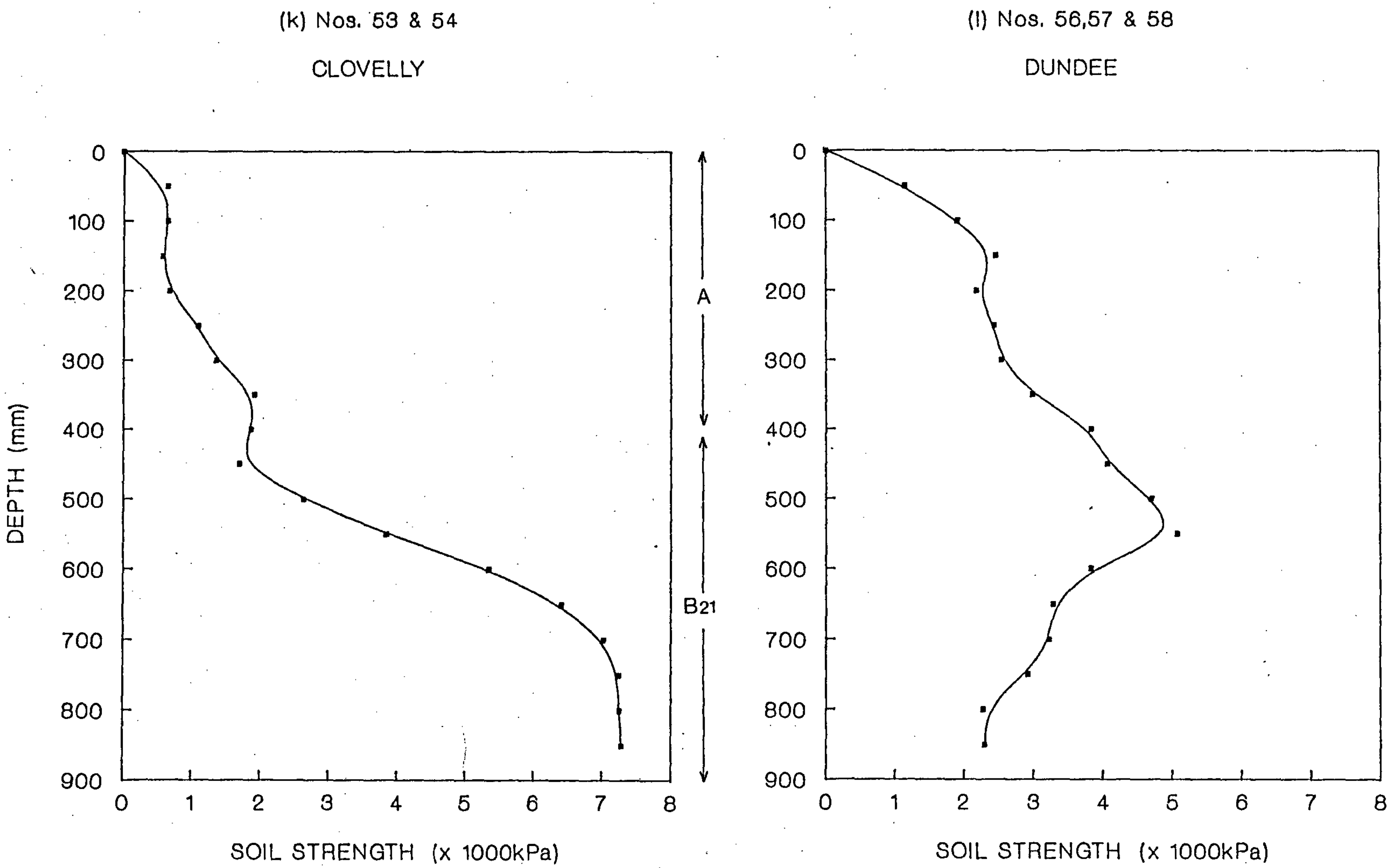


Fig. 4.3. Continued.

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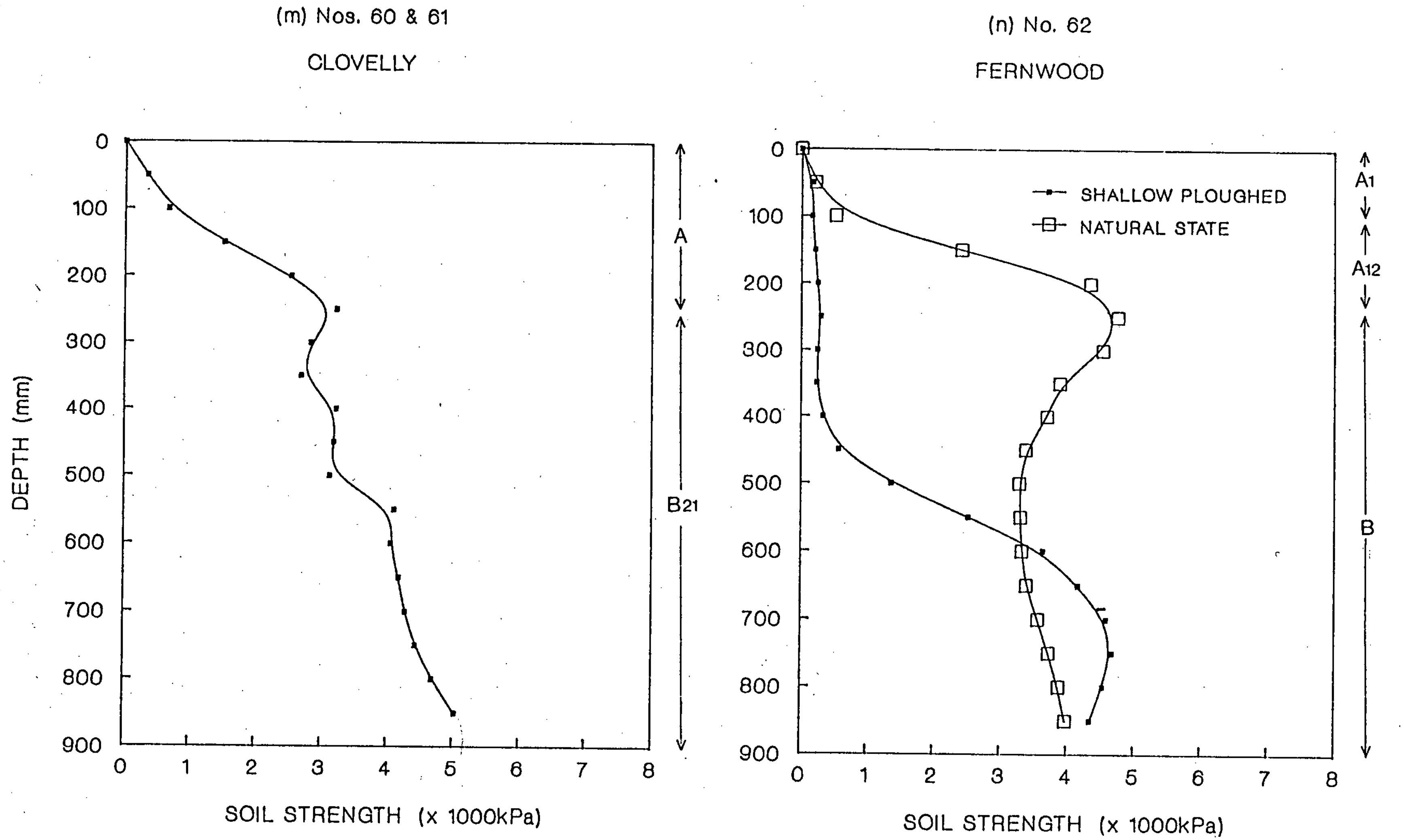


Fig 4.3. Continued.

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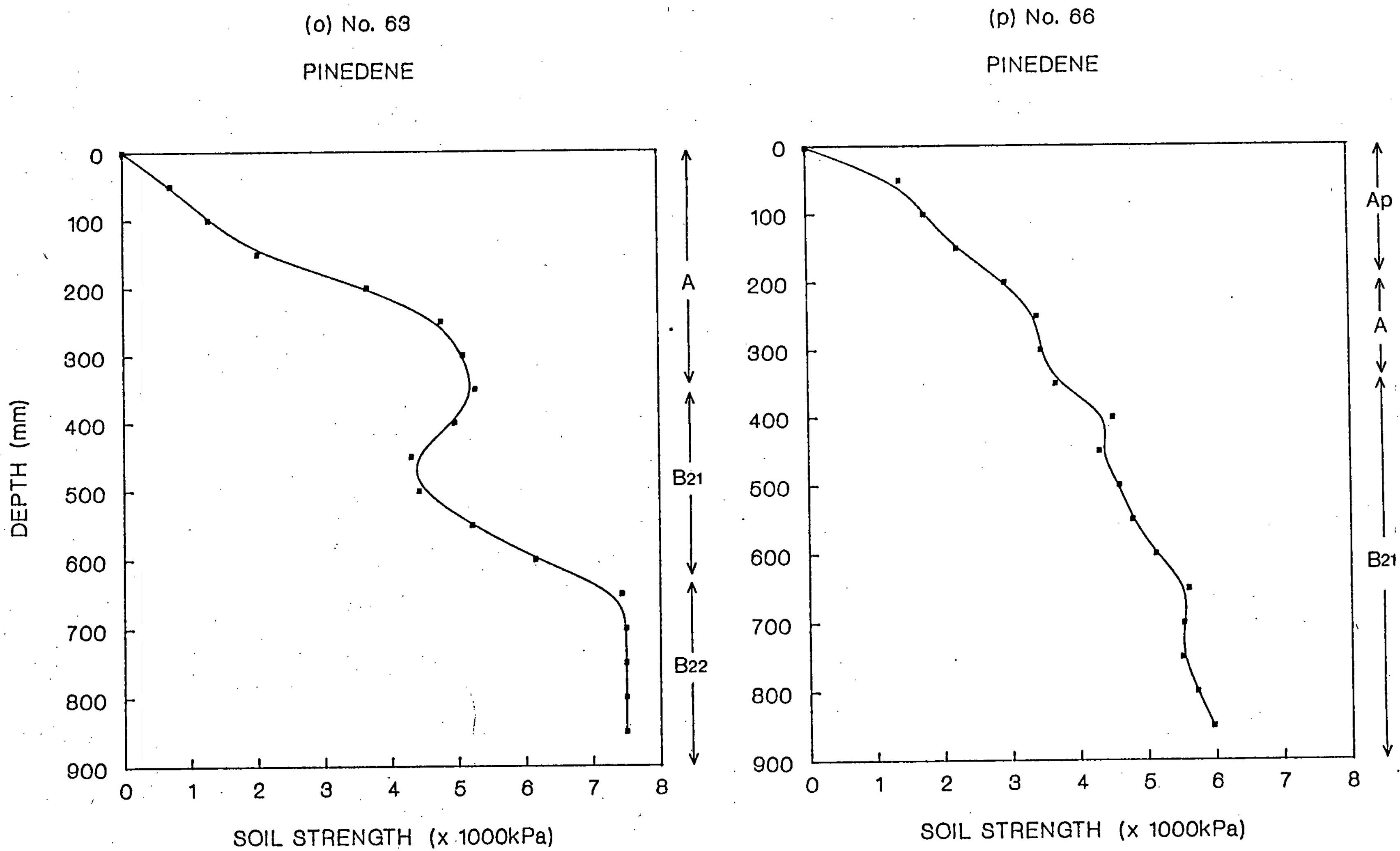


Fig. 4.3. Continued.

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(q) No. 71

CLOVELLY

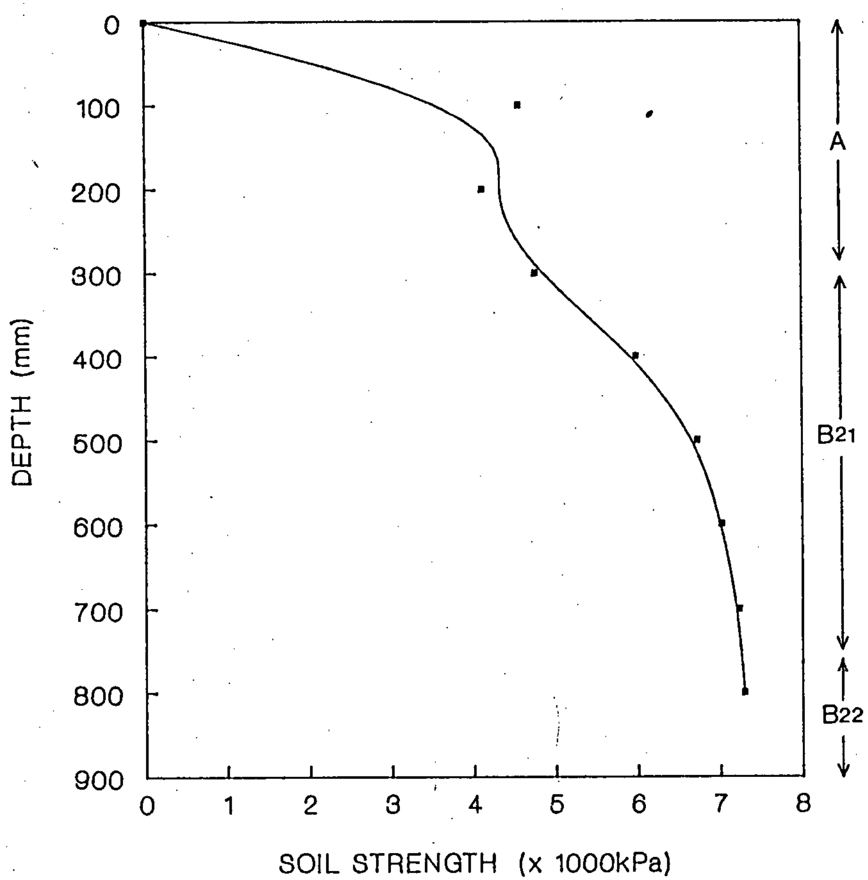



Fig. 4.3. Continued.

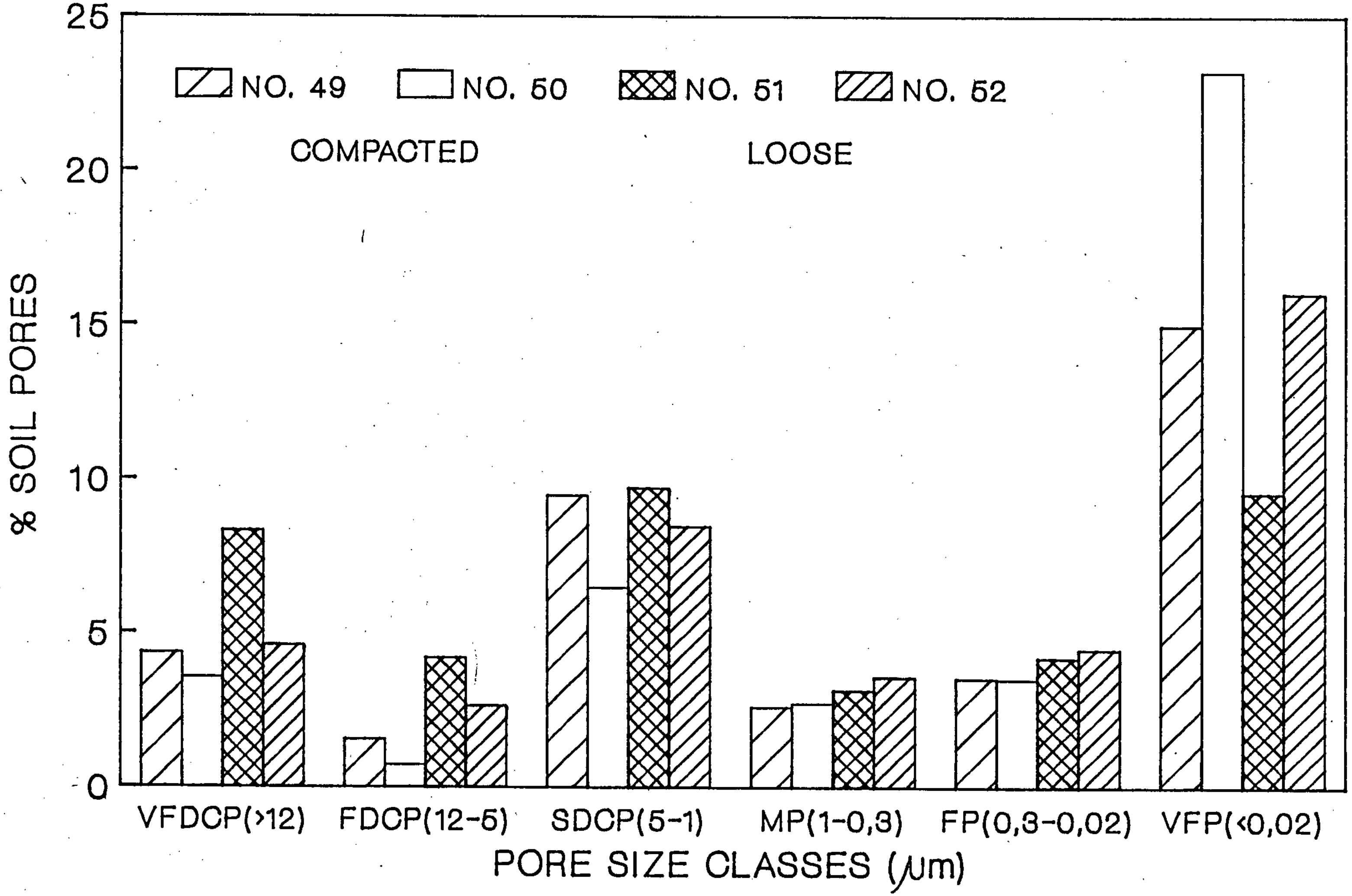
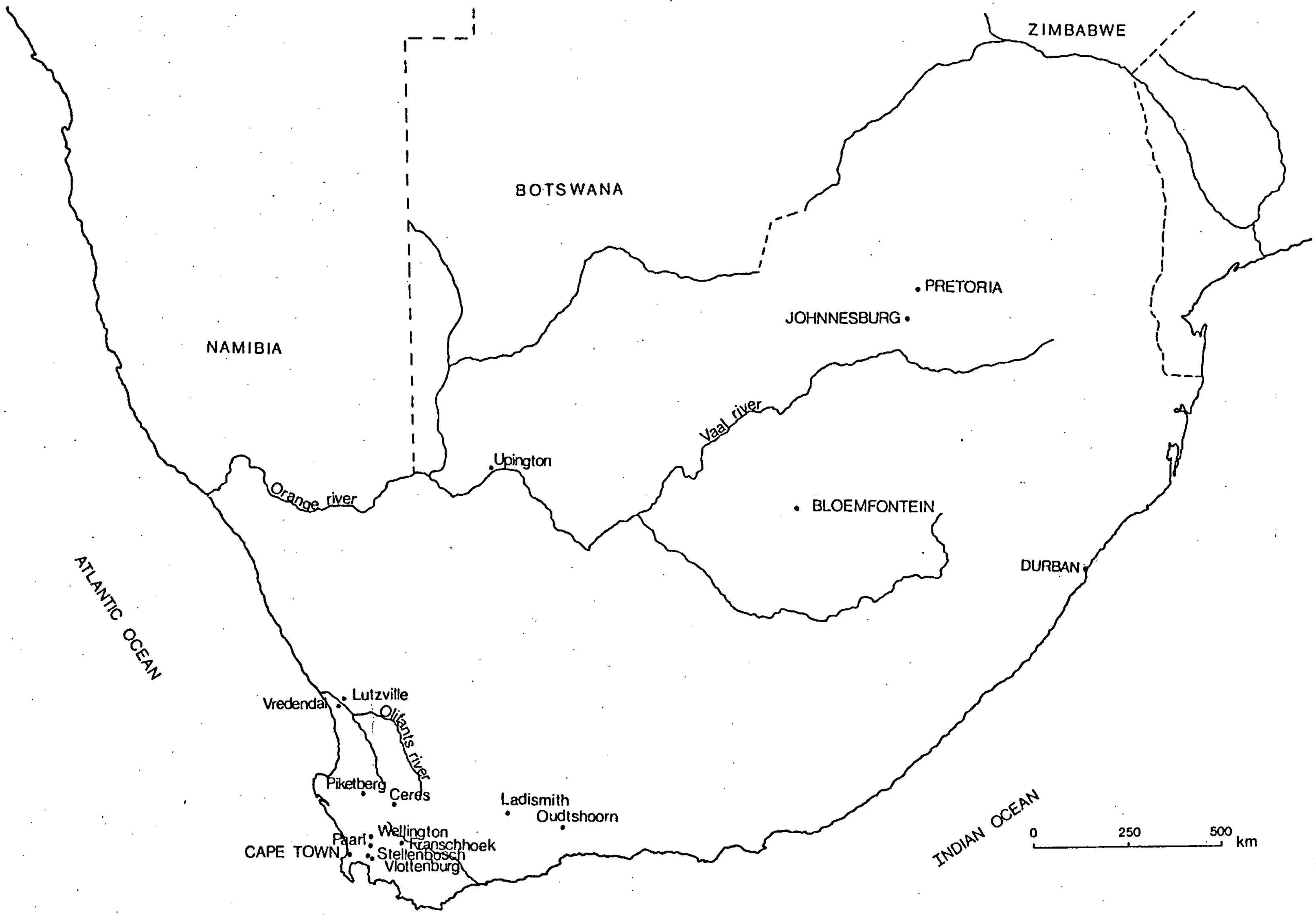



Fig. 4.4. Pore size distribution for "compacted" and "loose" Oakleaf soils from Ladismith. (For abbreviations of pore size class names, please refer to text.)




Map 4.1. Sampling localities in the principal wine regions of the Republic of South Africa.

# CHAPTER 5

## RELATIONSHIP OF SELECTED SOIL CHEMICAL AND PHYSICAL PROPERTIES TO SOIL COMPACTIBILITY

### ABSTRACT

A total of 71 soil samples representing the main soil types in South African vineyards were collected from various locations. Data on the chemical and physical properties of the soils, *i.e.* pH, cation exchange capacity (CEC), organic carbon content (OC), Proctor maximum bulk density (MBD), modulus of rupture (MOR), aggregate stability (AS), air-to-water permeability ratio (AWR), complete textural analysis determinations and statistical measures calculated from this data, were subjected to scatterplot and simple regression analyses in an effort to establish relationships with soil compactibility. Multiple regression equations were developed to predict MBD from particle size analysis data and distribution measures . The use of AWR and MOR together with such predictions were successful in grouping soils into various compactibility classes as expressed by MBD. Low-lying, hydromorphic soils and silt rich, alluvial soils with relatively high pH's were separated from the rest of the soils as having different compaction characteristics. The effect of organic matter content on MBD *per sé* could not be established. A preliminary AWR threshold value of 40 for artificially packed soils is suggested to distinguish between structurally stable and unstable soils. Wet sieving was found to be unsuitable to describe aggregation for this type of study.

### 5.1 INTRODUCTION

The many facets of the compaction problem in the vineyard soils of the Republic of South Africa (RSA) were described in Chapter 4 of this dissertation. It was furthermore pointed out that a more quantitative approach should be followed in order to improve the understanding of the problem of soil compaction in vineyards.

Bulk density (BD) , structural stability, modulus of rupture, *etc.* are terms typically used to describe the physical condition of the soil. According to Cassel (1982), BD was spatially variable due to soil texture, organic matter content and soil structure, whereas the BD variability within the profile was due to soil morphology. The extent to which a soil will compact is determined by applied forces (Larson *et al.*, 1980), particle shape (Brady, 1974), organic matter content (Adams, 1973), particle size distribution (Bodman and Constantin, 1965; Van der Watt, 1969; Moolman, 1981; Swee, 1982) and water content (Soehne, 1958; De Kimpe *et al.*, 1982). Several investigators presented equations to predict BD's based on one or more soil properties; for instance Saini (1966) and Adams (1973) used organic matter while others (Van der Watt, 1969; Heinonen, 1977; Moolman, 1981; Gupta and Larson, 1982) utilised textural data.

Modulus of rupture (MOR) is related to aggregate stability (AS) and is widely used as a parameter for assessing a soil's structural stability (Sahlih *et al.*, 1988). According to Hutson (1971), factors such as particle size distribution, clay mineralogy, state of aggregation, wetting and drying and chemical properties of the soil affected MOR. "The classification of a soil as having a structure problem in terms of management practice obviously involves a consideration of its natural MOR and its susceptibility to structural degradation ...." (Aylmore and Sills, 1982).

Changes in BD and soil-water-air relationships have been recognised as the reflection of changes in soil structure. By definition, the structure of a soil should reflect the nature of its component primary particles and the extent to which they have aggregated into larger units. It was therefore assumed that structural stability, and factors affecting structural stability, might relate to soil compactibility. According to Strickland *et al.* (1988), aggregation and aggregation mechanisms probably differ among soil types and particle size classes of a given soil, and therefore one particular technique of determining AS does not necessarily apply to all soils. In theory one of the more promising methods to determine AS involves wet sieving, but unfortunately in practice it is difficult to obtain reproducable results (Harris, 1971). Hutson (1983) reported that, under South African conditions, sandy soils, soils high in organic matter content and sesquioxide rich soils generally had a high structural stability during wetting and drying, while the stability of soils containing swelling clays or high exchangeable sodium levels was low. In contrast, the organic carbon and free iron oxide contents of the South African soil samples analysed by Van der Merwe (1973) were low and had a negligible effect on structural stability.

Hutson (1983) recommended determination of the air-to-water permeability ratio (AWR) as a screening technique to determine structural stability. Although he could not define a fixed threshold value to distinguish between soils it was concluded that the AWR values could be used as additional evidence for classification purposes, *e.g.* for structural stability in soil surveys. According to Reeve (1965), an AWR-value of one indicates a theoretical maximum stability, while values greater than one imply deterioration of soil structure.

The objective of this research was to compare a number of selected soil physical and chemical properties in order to assess the relative importance of them in identifying and quantifying soil compactibility. For this purpose a population of samples representing different degrees of compaction and which was representative of the most important vineyard soils were used. It was hypothesised that two types of soil properties influence soil compactibility: one is based on the mechanical composition of the soil, and the other is based on the degree of aggregation and the stability of the aggregates.

## 5.2 MATERIALS AND METHODS

A total of 71 soil samples comprising of a wide textural range and representative of various soil types and different degrees of compaction were collected in the most important viticultural areas of the RSA. The sampling procedure and the analytical methods were described in full in Chapter 4. General background and morphological information of the samples are given in Appendix 1 and Table 4.1.

Further to the methods outlined in Chapter 4, univariate summary statistics, *viz*. minimum, maximum, mean, median, lower quartile and upper quartile values, were calculated in order to describe the raw data (Appendix 8). Although many soil properties were measured, only those properties thought to be related to and demonstrative of compaction will be discussed in this chapter.The inter and intra relationships (Table 5.2) of chemical- (Table 4.2), physical- (Table 4.3) and particle size analyses data (Appendices 2 and 3) were studied by regression analysis. Elementary statistical techniques were used to identify relationships, if any, between the various parameters. First, a correlation matrix between all pairs of properties was calculated to investigate the relationships between different combinations of variables. Linear regression analyses were subsequently applied to some pairs of variables provided that their correlation coefficients exceeded an arbitrarily chosen r-value of 0,40. In addition, bivariate scatterplots were made to study the degree of association between those pairs of properties not subjected to regression analysis.

Due to the wide variety of soil types studied, "outlier" points were invariably present, which reduced the point cloud size by forcing the vast majority of points into a small region. Therefore, plots with and without outliers were made during initial data interpretation. It was decided not to apply transformations, like square roots and logarithms, because transformations are not of much value in cases where outliers are present (Daniel and Wood, 1980). In this dissertation the term "outlier" is not being used in its statistical meaning, *i.e.* being "any observation that appears surprising or discrepant to the investigator" or " any observation that is not a realization from the target distribution " (Beckman and Cook,1983). It is meant to be an observation that deviates markedly, but for obvious and/or explicable reasons, from the other members of the population, and as such is representative of typical variability in a field situation. In an effort to isolate different soil "groups" an interactive oulier rejection routine was employed during the initial linear regression data analysis. In the final models/plots no soil was excluded as being an oulier.

Statistical measures for the particle size distribution data were calculated (Krumbein and Pettijohn, 1938) and are presented in Appendix 9. In addition to the arithmetic mean, moment coefficient of skewness, moment coefficient of kurtosis (also used by Moolman, 1981) and the geometric particle-size standard deviation (GDEV), as described by Shirazi and Boersma (1984), were calculated. A backward, stepwise variable selection regression method was followed after the recommendations of Draper and Smith (1981). The backward elimination procedure essentially attempted to remove all x-variables without substantially increasing the variance. The maximum adjusted $R^2$ criterion was used to obtain the "best subset" of predictor variables for a "best fit" line using multiple regression for the prediction of MBD (Draper and Smith, 1981 - Eqn. 2.6.11b and p. 303). As a matter of clarity, the reader is reminded that linear regression was used to study relationships between pairs of variables and that multiple regression was used to predict MBD from textural data and its statistical measures as independent predictor variables.

## 5.3 RESULTS AND DISCUSSION

The chemical- (Table 4.2) and physical- (Table 4.3 and Table 5.1) properties of soil, together with the particle size data (Apendices 2, 3 and 9), represented a large and detailed set of information. There are many aspects of this data that can be discussed, however, in this paper the discussion is restricted to correlations relevant to soil compaction.

### 5.3.1 Chemical properties

Correlations of some pertinent chemical properties are summarised in Table 5.2. Both pH and cation exchange capacity (CEC) correlated well with the other chemical properties, and could be used to identify soil groups clearly differing in chemical characteristics. However, it is doubtful whether they can be used as predictors of other chemical properties that might be related to compactibility. As was noted in Table 4.2, the sample population generally has low pH's, CEC's and organic carbon contents, the exceptions being semi-arid soils from Lutzville, Upington, the Southern Cape and Piketberg (Sample nos. 1, 41, 49, 50, 51, 52, 56, 57, 58, 64, 66) and some of the low-lying hydromorphic soils (Sample nos. 3, 14, 15, 16, 67). Likewise, the Ca-status was generally low (Table 4.2) which explains the strikingly low correlation thereof with other soil properties. Exchangeable Na and Mg, are usually reported to have a negative effect on soil structure (Aylmore and Sills, 1982; Hutson, 1983), but are of little practical importance in this study due to their generally low values.

Despite the poor relationship between the chemical properties and soil texture, a linear regression of CEC *versus* percentage clay fraction (<2 mm diameter basis) is presented in Figure. 5.1, solely for classification purposes. Both the group of soils from the semi-arid areas and the hydromorphic group of soils, as mentioned above, clearly separate themselves from the rest of the sample population by falling above the regression line. Except for their overall higher pH's, they also in general have higher organic material contents (Table 4.2). Omittance of these soils from the data set increased the correlation coefficient (r) to $0{,}81^{**}$. The more unconventional regression of CEC on fine silt plus clay (<0,020 mm), with $r = 0{,}55^{**}$, essentially resulted in the same grouping of the soils, except for soil nos. 14 and 17 which were not so prominently separated as in the first plot. These relationships gave the first indication that the hydromorphic soils and soils from the semi-arid irrigation areas separated from the rest of the soils.

### 5.3.2 Mechanical soil composition

The spread of soil textural classes is summarised in Figure. 4.1 and listed in Table 4.1. In Appendix 8 selected summary statistics of the particle size data are presented, while the mass percentage of soil in each particle size class is given in Appendix 2 (<2 mm diameter basis) and Appendix 3 (<6 mm basis); with the statistical measures of the particle size distribution results presented in Appendix 9. The ranges of the various textural classes in Appendix 8 are typical of the most prominent vineyard soils in South Africa. The high gravel (6,00-2,00 mm) contents of sample nos. 6 (47,13%) and 40 (61,95%) must be noted for further discussion. Because it was thought to be a better representation of actual field conditions, the particle size results were mostly expressed on a smaller than 6 mm diameter basis (<6 mm). It was for the same reason that particles, which passed through a 6 mm sieve, were used for MBD, AS and AWR tests. (In cases where the fractions on a smaller than 2 mm diameter basis (<2 mm) were used, like MOR, it will be stated clearly).

The coefficient of skewness is a measure of peakedness or symmetry, while the coefficient of kurtosis is a measure of tailedness of the frequency distribution curves of particle size data when for instance absolute mass percentages of particles are plotted *versus* the phi-scale of particle size classes (Krumbein and Pettijohn, 1938; Moolman, 1981). These two parameters were used to interpret the cumulative particle size distribution curves in Appendix 4. For a normal distribution, kurtosis has the value 3 and skewness has the value 0 (Snedecor and Cochran, 1980). Consequently, kurtosis (KUR) can be used as an index of the grading of soils. Soils with flattened and smooth distribution curves have low coefficients of kurtosis, which apparently increase the compactibility of a soil (Moolman, 1981). The geometric standard deviation (GDEV) is also a nondimensional value that may be used as an additional measure to reflect the degree of sorting (uniformity or diversity of particle size) of a soil sample or the degree of spread of the particle size distribution curve (Shirazi and Boersma, 1984). The GDEV of a perfectly homogeneous mixture, such as perfect spheres, is unity. If particle size distribution plays an important role in soil compaction, then the statistical descriptive measures of particle size distribution should be related to, *inter alia*, BD. The two parameters, KUR and GDEV supplemented each other as aids to visualise textural data. The correlation coefficients (r) between the particle size classes and these two parameters are as follows:

| Variable | KUR | GDEV |
|---|---|---|
| total sand | +0,82** | - 0,68** |
| coarse sand | +0,60** | - 0,09 |
| medium sand | +0,55** | - 0,35* |
| fine sand | +0,26 | - 0,54** |
| silt + clay | - 0,81** | - 0,32* |
| clay | - 0,81** | +0,68** |
| GDEV | - 0,64** | - |

Further reference to the nature of the textural data will be made in the discussions to follow.

### 5.3.3 Maximum compaction

Plots of maximum compaction versus water content are presented in Appendix 5 while the actual maximum bulk densities (MBD) and critical water contents (CWC) are presented in Table 4.3. The term critical water content was preferred to the term optimum water content because in terms of soil tillage this water content is of critical importance. The compaction curves followed the usual Proctor-type shape. The CWC for the sample population ranged between 4,32 and 18,5 g 100 $g^{-1}$ with corresponding MBD values between 1,600 and 2, 080 Mg $m^{-3}$ (Appendix 8). An average increase of only 13,6% (0,225 Mg $m^{-3}$) in MBD over field bulk density (FBD) was measured. This illustrates that generally high FBD's occur in a wide spectrum of vineyard soils because on average the natural FBD is only slightly lower than the average MBD obtained by applying a relatively high compactive force.

The relationship between CWC and MBD is given in Figure 5.2. MBD is inversely proportional to CWC, *i.e.* the highest MBD's are obtained at the lowest CWC's. This is a confirmation of the unique relationship between compactibility and water content, *i.e.* each soil has a specific CWC value. Sample no. 40 is an outlier with 61,95% gravel and a particle density of 2,87 Mg $m^{-3}$, which explain the inflated MBD value. The explanation for the positions of the different soils on this curve is not straightforward. For instance, some of the sandy loams (*e.g.* sample nos. 6,18, 35, 47) packed to the highest BD's at the lowest water contents, while for others (*e.g.* sample nos. 49, 51, 57, 65) exactly the opposite is true. The possible role of clay mineralogy in explaining these differences was not investigated in this study. The soils from the hot semi-arid areas (Sample nos. 1, 49, 50, 51, 52, 56, 57, 58) grouped to the lower right corner of Figure 5.2. Soil no. 48 has a below average particle density (2,63 Mg $m^{-3}$), but the reason why this virgin soil compacted to such a low MBD is not clear. It is also uncertain why the four coarse sands (Sample nos. 12, 20, 45, 46) grouped separately. If it had been due to their particular particle size distribution (high kurtosis, high skewness, high arithmetic mean), one would have expected at least sample nos. 10, 11 and 69 to group with them for they had comparable values. Texturally these four soils fall among the lower quartile soils with clay contents of less than 7,1% (Appendices 3 and 9), and also had low organic matter contents - conditions under which factors such as particle shape possibly can dominate compactibility (Cruse *et al.*, 1980). Sandy soils are furthermore not so specific for the water content at which they compact to their maximum. Exclusion of sample nos. 12, 20, 40, 45 and 46 as outliers from the data set presented in Figure 5.2, improved the correlation coefficient (r) for CWC *versus* MBD from $-0.61^{**}$ to $-0{,}83^{**}$. Although the relationship between CWC and MBD is not as good, these findings are in agreement with the results of de Kimpe *et al.* (1982).

The relationship between organic matter content (OM) and bulk density had been studied in the past (Adams, 1973; De Kimpe and McKeague, 1974; Wang *et al.*, 1978; De Kimpe *et al.*, 1982) and found to be significant. In the present study no clear relationship emerged between OM and BD, and the data points were scattered almost at random with no separation amongst previously identified soil groups (figure not shown). The occurrence of MBD's of less than 1,72 Mg $m^{-3}$ (Sample nos. 1, 48, 56, 57 and 65) can, except for sample no. 65, not be ascribed to OM. A positive correlation between organic matter and clay content (Jenny, 1941; Banin and Amiel, 1970) could not be established in this study (r = -0,15) and might be explained by the wide selection of samples. The generally low organic matter contents (average = 0,81%) are characteristic of South African vineyard soils and are due to high soil temperatures. Unlike the results of de Kimpe *et al.* (1982), no good association (r = -0,25) was found between particle density and OM. (It should be noted that in line with the method of Blake (1965), organic matter was not removed before measuring particle density). The soils from the semi-arid irrigation areas (Sample nos. 41, 49, 50, 51, 52, 56, 57, 58) grouped together on the scatterplot of particle density *versus* OM, as did the hydromorphic soils 14, 15, 17 and 18 (not illustrated - compare Appendix 6 and Table 4.2). The soils from the semi-arid irrigation areas listed above had the highest particle densities while some of the low-lying, hydromorphic soils (Sample nos. 3, 14, 15, 16, 17, 18, 67) had the lowest particle densities. Sample no. 65 had the highest organic matter content (2,11%). These facts must be kept in mind for further discussions of compactibility because de Kimpe *et al.* (1982) stated that dry bulk density is directly proportional to particle density and showed the mathematical logic why high organic matter contents will decrease BD.

The CWC related positively both to the total silt plus clay (< 0,053 mm diameter ) content ($r = 0{,}68^{**}$;

S.E.E. = 2,19) and fine silt plus clay (<0,020 mm diameter) fraction ($r = 0{,}68^{**}$; S.E.E. = 2,20). The relationship of CWC with the clay fraction (<0,002 mm diameter) is presented as an example in Figure 5.3. Again, like in Figure 5.2, the two coarse sands (Sample nos. 12 and 20) grouped together. Some of the samples from the semi-arid/irrigation areas (Sample nos. 1, 49, 50, 51, 56, 57, 58) had higher CWC's than were expected from their clay contents. This is *inter alia* probably due to their slightly higher organic matter contents (Table 4.2), an explanation which also applies for sample no. 10 (coarse sand), and especially for sample no. 65 (fine loamy sand). Exclusion of the abovementioned 11 soils from the sample population improved the linear relationship from $r = 0{,}68^{**}$ to $r = 0{,}84^{**}$, which is more in line with the literature (Henning *et al.*, 1986). Sample no. 9 is a deep lying, poorly weathered C horizon with micaceous clay minerals which, together with the 15,2% clay content, resulted in the relatively high CWC.

A plot of MBD on the clay fraction ($r = -0{,}23$), or any other individual textural class, did not produce a good fit (not shown). The points were widely scattered with no definite grouping or logic arrangement. In contrast, Henning *et al.* (1986) reported the following relationship ($r = 0{,}98$) between clay and MBD ($n = 7$ soils):

$$\text{MBD (kg m}^{-3}) = -0{,}74(\%\ \text{Clay})^2 + 28{,}74(\%\ \text{Clay}) + 1692{,}13;$$

while Gupta and Larson (1982) established the following relationship ($r = 0{,}82$) for compacted bulk density (CBD) at 50% saturation for 40 soils with clay contents ranging between 0% and 75%:

$$\text{CBD (Mg m}^{-3}) = -3{,}468 \times 10^{-5}(\%\ \text{Clay})^2 - 5{,}560 \times 10^{-3}(\%\text{Clay}) + 1{,}544.$$

A general conclusion based upon the present scatterplots, mentioned above, is that, in accordance with results of van der Watt (1969), maximum potential compaction (MBD) decreases with increasing silt plus clay (<0,053 mm) content of the soil. This was somewhat in disagreement with results of Moolman and Weber (1978) who found the opposite for their specific set of soil samples. Thus, the accurate prediction of MBD with such a wide scatter of textural classes, and for such a wide variety of soil types, would be an achievement in itself.

The possibility to predict MBD by using several combinations of variables ( > 10 variables per set) from the textural data was systematically investigated with a stepwise regression (backwards selection) procedure. Different variables were manually removed from a particular set if the the calculated partial F-test value for a variable was smaller than the preselected significance level of $F = 4$. Examination of the correlation matrix for the textural data, of which an example is presented in Table 5.3, illustrated the theoretical restriction of particle size data, *viz.*: $X_1 + X_2 + X_3 + ... + X_n$ = constant ($\pm$100). This meant that any mass percentage, $X_i$, of the *ith* particle size class was theoretically dependent on $X_1$, $X_2$, $X_3$ ... and $X_n$. In simple terms, if clay and/or silt increases, sand decreases. Further, the statistical measures presented in Appendix 8 also correlated with the particle size distribution data from which it was calculated. For this reason, it was decided to accept the regression equation that was the most economic in terms of the number of independent variables. This is the only way to reduce the possibility that two or more interdependent variables, which by coincidence might be a characteristic of a particular sample population, are simultaneously used as predictor variables. For example, kurtosis and skewness ($r$ = 0,93, Table 5.3) should not both be used in the same equation as predictors of MBD.

As suggested by Draper and Smith (1981), personal judgement was used to exclude those variables that had a minor effect on the explained variation in MBD. With the backward selection procedure it was never necessary to force a variable from the final model for the present data, provided that meaningful combinations of variables were entered in the first place. In cases where only one subfraction of a particle size class such as fine sand, was selected by the model, the other fraction was forced into the model but only if it could improve $R^2_{adjusted}$, *e.g.* the 2,00 to 1,00 mm size fraction (FR16) of the coarse sand (2,00-0,50 mm) was forced into the model when only the 1,00 to 0,50 mm subfraction (FR26) and gravel (6,00-2,00 mm = GR) were selected. This was an attempt to investigate if the inclusion of the complete defined textural fraction could improve the prediction compared to when only a subfraction of it was included.

An example of the changes in the coefficient of determination ($R^2$) for the prediction of MBD when different textural variables were used is given hereunder (variable names and particle size fractions as in Appendices 2 and 3 on pages A.8 and A.11, respectively):

| Full set of variables | | Best subset | |
|---|---|---|---|
| Initial | $R^2$ | Final | $R^2$ |
| 1) 10 Fractions <2 mm | 0,28 | FR1, FR3, FR6, FR8 | 0,23 |
| 2) 10 Fractions <6 mm | 0,39 | FR26, FR46, FR56, FR66, FR96, FR106 | 0,37 |
| 3) Set 2 + Gravel | 0,43* | FR36, FR46, FR96, Gravel | 0,38 |
| 4) Set 3 + GDEV6 | 0,43* | FR36, FR46, FR96, Gravel | 0,38 |
| 5) Set 3 + KUR6 + SKH6 | 0,63** | FR26, FR36, FR106, KUR6 | 0,61** |

The results of the multiple regression analyses suggested that for the prediction of MBD, the particle size data expressed on a < 6 mm diameter basis are more suitable than the < 2 mm data. The regression model could be improved further by the inclusion of first, the 2 to 6 mm gravel fraction and second, the statistical measures of the particle size distribution curve. It can furthermore be inferred that for this particular sample population, kurtosis is the most meaningful statistical measure to include in the regression equation *(e.g.* it could not be replaced by GDEV), which is in accordance with Moolman (1981) who reported that soils with high kurtosis values compacted to lower MBD's.

The final equation selected is given in Table 5.4a. With variables, FR16 (2,00-1,00 mm) and FR46 (0,30-0,25 mm), forced into the model to include the complete coarse and fine sand fractions, the final equation changed to that in Table 5.4b. It resulted in a slightly lower $R^2_{adjusted}$-value and the S. E. E. differed only in the third decimal. The last equation given in Table 5.4 is probably more meaningful because the different arbitrarily divided fractions within the coarse sand (2,00-1,00 mm; 1,00-0,50 mm) and within the medium sand (0,50-0,0,30; 0,30-0,25 mm) classes are now added together. However, in terms of the maximum attainable $R^2_{adjusted}$ and minimum number of independent variables, preference was given to the equation listed in Table 5.4a. This equation was chosen as the final regression model for the prediction of soil compactibility as reflected by MBD. The correlation matrices for the coefficient estimates of the different regression models as presented in Table 5.4 are given in Table 5.5.

The inclusion of the coarse sand and clay in the regression equation was in agreement with the results reported by van der Watt (1969), while the inclusion of kurtosis is in accordance with research by Moolman (1981). The exclusion of the fine sand fractions is at variance with the general belief (Crossman & Cline, 1957; Milford *et al.*, 1961; Bennie, 1972) that these fractions are determinants of compactibility. Moolman and Weber (1978) also suggested that it is the size distribution of the particles and not the fine sand that determines compactibility of the fine sands (>55% fine sand) they investigated. In the present study, this does not mean that fine sand *per se* is unimportant. It is quite likely that its omittance is due to the nature of the interrelationships between fine sand and another already used predictive textural variable in the particular sample populations (compare FR56, FR66 and FR76 in Table 5.3). For example FR56 (0,25-0,106 mm of fine sand fraction) correlates with gravel ($r = 0{,}46^{**}$), already included in the model, and so does FR66 (0,106-0,075 mm of fine sand fraction) with both FR26 ($-0{,}49^{**}$) and FR36 ($-0{,}46^{**}$), while FR76 (0,075-0,053 mm of fine sand fraction) correlates with the already included FR26 ($r = -0{,}44^{**}$) and FR36 ($-0{,}44^{**}$).

The normal probability plot of the residuals for the final model showed slight departure from normality which is also confirmed by a coefficient of kurtosis = 4,16 and a coefficient of skewness = -1,32 (Fig. 5.4). (For a normal distribution, kurtosis has the value 3 and skewness has the value 0 according to Snedecor and Cochran, 1980). The practical importance for the present study of such departure from normality is not clear. Roughly 40% of the variation in MBD could not be explained by the selected "best fit" model ($R^2$ = 0,61$^{**}$, Table 5.4a), but the plot of predicted values *versus* the measured MBD for 71 soils in Figure 5.5, however, showed a fairly good relationship. It must be kept in mind that the final model was developed using the results of all 71 samples. This included those soils previously identified as "outliers," *i.e.* sample nos. 4, 16, 65 (unstable and wet); 9 (unweathered micaceous clay); 48 (virgin soil); 56, 57 (soils from irrigation areas) in Figures 5.1 (CEC), 5.2 and 5.3 (CWC). Only two samples had residuals beyond $3\sigma$ = 0,19 Mg $m^{-3}$: No. 9 (-0,19) and no. 48 (-0,26). Both of these two soils represent relatively unweathered material with low KUR6 values (<1,9) and high GDEV6 values (>13,3), which is the reason why such high BD's are predicted by the model in Table 5.4a.

The "accuracy" with which MBD was predicted for the majority of samples is surprising considering that the model included all the mentioned "outlier" soils (Fig. 5.5). The following samples were overpredicted by more than 1 x S.E.E. = 0,07 Mg $m^{-3}$ of the measured values: Sample nos. 56, 57 and 65, whereas sample nos. 4, 15, 16, 35 and 71 were underpredicted with more than 1 x S.E.E. The samples that were well-predicted within that arbitrary limits represent a wide textural range and different soil types. Attention is drawn to the accuracy with which the MBD's of soils containing high percentages of gravel (figures between brackets = gravel contents) were predicted *e.g.* sample nos. 6 (47,1%), 7 (27,3%), 8 (15,7%), 26 (34,3%), 27 (19,6%), 29 (33,6%), 31 (28,7%) and 40 (61,95%). It is, therefore, concluded that the multiple regression model developed in this study (Table 5.4a) is successful in predicting MBD's for the present sample population (Fig. 5.5), except for some low-lying hydromorphic soils (Nos. 4, 15, 16, 65), some soils from the semi-arid irrigations areas (Nos. 56, 57), young unweathered soils (Nos. 9, 48) and soils with other observed structural problems (Nos. 35, 71).

If the problems associated with the measurement of FBD (Cassel, 1982) are taken into account, the accuracy of prediction obtained from the multiple regression model (Table 5.4a) is acceptable as a first approximation to, at least, classify soils for their maximum compactibility (MBD). As was already mentioned, the scatterplot of MBD *versus* the clay content showed a rather wide scatter of points. It was therefore postulated that inclusion of the clay content in the regression equation, together with the use of the smaller than 6 mm database, may to some extent compensate for structural properties that might influence the compactibilities of the individual soils - in other words, improve the prediction of MBD. Both Van der Watt (1969) and Moolman (1981) expressed their concern about the non-quantification of soil structure in their compaction studies.

### 5.3.4 Structural properties

Structural breakdown implies formation of smaller particles or units, which can influence the packing of soils, and hence, its compactibility. Therefore, a study of structural properties might explain some of the observed BD's. Several parameters were employed to measure the structural characteristics of the soils in an effort to identify and classify the soils for compactibility by other means than just BD, texture and morphology. Literature reveals that aggregate stability is affected by the contents of organic matter, iron oxides, aluminium oxides and -hydroxides, and other sesquioxides (Monnier, 1965; Desphande *et al.*, 1968; Greenland *et al.*, 1968; Khrisna Murti and Rengasamy, 1976; Ange *et al.*, 1977). It was however, not the purpose of this investigation to study the microscopic interactions of these constituents on soil structure, but rather to measure the result of these constituents as they acted in different soils.

<u>Air-to-water permeability ratio (AWR)</u>: The relationship between air and water permeability, a dimensionless figure which reflects structural stability upon wetting, is depicted in Figure 5.6. Lower AWR values indicate a closeness between air and water permeability values and thus higher structural stability. Higher AWR values reflect a decrease in permeability of soils during water flow and thus less structural stability.

According to Hutson (1983), it is difficult to define threshold AWR values. However, for the present data set lower quartile-, median- and upper quartile AWR values of the sample population can be used to group the samples into different stability classes. Approximate threshold values between classes were selected as 20, 40 and 70 (Fig. 5.6) for the population used in this study (Appendix 8). The stability classes are the following: Stable (1-20), variable stable (20-40), variable unstable (40-70) and unstable (>70). Although empirical, these classes roughly conformed with field observed stabilities. All the sands and loamy sands (listed in Table 4.1), along with the red and yellow soils (Sample nos. 29, 30, 39, 44, 53, 54), were sorted into the first group (AWR <20). Although, sample nos. 60 and 61 were at the time of sampling not expected to lie in this group, their grouping in this class may be due to their high total sand contents (>75% - Appendices 3 and 4).

As anticipated, the unstable category (AWR >70) included the following soils : 3, 13, 14, 15, 16, 17, 18, 35, 48, 66 (low-lying, hydromorphic soils); 41, 49, 50, 51, 52 (soils under long term flood irrigation from the semi-arid areas). Soils not expected in this category were soil nos. 5, 6, and 21. The inclusion of these soils in the unstable group may be that sample no. 21 becomes very hard upon drying, soils 5 and 21 had surface crusts and high BD's at the time of sampling, and sample no. 6 has the lowest air permeability (45) of all the samples (Appendix 1). The high MOR2 values for soil nos. 6 and 21 were already noted in Chapter 4 (Table 4.3).

The positions of soils 6 (AWR = 166) and 7 (AWR = 53) in Figure 5.6 were surprising because in the field, they are not considered as being unstable, although they have relatively high MOR2 values - No. 6 = 101 kPa and No. 7 = 191 kPa (Table 4.3). Note also the positions of the variable unstable samples, that is soil nos. 22 (237,7); 24 (92,1) and 26 (89,9), which all are soils that get very hard upon drying. Of these three soils only 22 has a very high MOR2 (figures between brackets in kPa). Based on the results of Figure 5.6, together with practical experience, a stability threshold AWR value of 40 is suggested to separate soils according to structural stability. Hutson (1983) proposed a threshold value of 20.

The correlation coefficient of AWR with other soil properties reported in this study was not significant, which was surprising for at least the AWR *versus* MBD relationship. Water plays several important roles in the compaction process through its effect on structural stability, which in turn influences both AWR and compactibility. In the present study, this was the first indication of the complex relationship between structural properties and compactibility. Nevertheless, in terms of compactibility AWR sorted the soils into logic groups.

<u>Modulus of rupture (MOR)</u>: The variation in MOR is illustrated by a plot of MOR1 (after one hour soaking time) *versus* silt plus clay content in Figure 5.7, and MOR2 (after 12 hours soaking time) *versus* CEC in Figure 5.8. These two figures, which are only examples of many other possible plots (not shown) for MOR, explained much about the spread in MOR values of the sample population. Nutall (1982) found that clay content is negatively related to crust strength (of which MOR is a measure) for some soils, but positively correlated for others. This might be one of the explanations for the wide scatter ($r = 0,15$) of points for a plot of MOR *versus* clay content (not shown) with the present data, which represented many soils. According to Aylmore and Sills (1982), a MOR1 value of 60 identifies soils with hardsetting characteristics. Soils that fit this criteria in the present population (Fig. 5.7) are: Sample nos. 3, 13, 14, 15, 16, 18 (low-lying, hydromorphic soils) and nos. 50 and 52 (soils of the irrigation areas). The agreement for some of the soils grouped by AWR (Fig. 5.6) and selected as outlier groups by MOR studies was quite remarkable while for others it was not so straightforward, which suggests different mechanisms of aggregation on different soils.

Many studies have been concerned with the effect of chemical soil properties on MOR (Hutson, 1971; Van der Merwe, 1973; Aylmore and Sills, 1982), and thus structural stability. Apart from their own results, these authors also quoted many other authors who established relationships between chemical soil properties, especially Na, and soil structure. The divergent chemical nature of the present sample population, expressed by CEC, caused much of the wide scatter in Fig. 5.8. Thus, when the soils from the irrigation areas (41, 49, 50, 51, 52, 56, 57, 58), with their different chemical properties (Table 4.2), were rejected as ouliers from the regression, the correlation (r) of MOR2 on CEC improved to $0,77^{**}$ compared to the previous $r = 0,63^{**}$.

The linear association between MOR and some of the soil properties can be summarised as follows:

| Variable | MOR1 | MOR2 |
|---|---|---|
| MOR1 | - | $+0,74^{**}$ |
| CEC | $+0,42^{**}$ | $+0,63^{**}$ |
| clay | +0,15 | $+0,45^{**}$ |
| kurtosis | $-0,31^{*}$ | $-0,57^{**}$ |
| silt + clay | $+0,52^{**}$ | $+0,74^{**}$ |
| fine silt + clay | $+0,48^{**}$ | $+0,68^{**}$ |

In general MOR , and especially MOR2, underlined the previously known structural instability of specific soil groups, *e.g.* sample nos. 3, 22, 49, 50, 51 and 14 to 18. Like AWR, MOR could be used to identify structurally stable soils, *e.g.* 44, 53, 54, and, to a lesser extent, also 56, 57 and 58.

Similar to the results of Aylmore and Sills (1982), there was too much scatter in the present data to relate MOR to any single soil property. The equation MOR2 = exp(5,5635 - 0,2737Kurtosis), with $r = -0,77^{**}$, described the relationship between MOR2 and soil textural data the best. While the importance of organic matter is generally acknowledged, variations in the amounts of total carbon are usually found to be insufficient to explain variation in structural stability (Greenland, 1971; Hussain *et al.*, 1985). This probably is the reason why no association was found between organic matter and MOR in the present study ($r_{MOR1}$ = 0,03 and $r_{MOR2}$ = 0,15).

Examples of stepwise multiple regression models to explain the variation in MOR are summarised in Table 5.6 and illustrated in Figure 5.9. A normal probability plot (not shown) of the residuals of these models confirmed normality . There were no residuals beyond $3\sigma$ (179,9 kPa). The reason(s) why sample nos. 8, 9, 56 and 65, as a group, was overpredicted are not clear. Sample nos. 5, 21, 28 and 31 are topsoils known to get hard upon drying, while sample nos. 15, 18 and 67 (hydromorphic soils) also got much harder during determination of MOR2 than was predicted. In general it may be concluded that, except for these few outlier soils, MOR can be predicted fairly well from CEC and textural data ($R^2_{MOR1} = 0,62^{**}$ ; $R^2_{MOR2} = 0,69^{**}$). In both cases fine silt (FR9) and clay (FR10) were included as independent variables.

MOR2 is related to MOR1 by the relationship: MOR2 = 2,37 MOR1 + 85,86 ($r = 0,74^{**}$; S.E.E. = 70,9 kPa). The following samples had MOR2 values at least 1 x S.E.E. higher than predicted from this linear relationship with MOR1: nos. 4, 41, 23, 3, 28, 32, 22, 31, 21, 67 (arranged in increasing order of deviation). This probably is an indication that particle cementation and/or additional structural degradation cause these high MOR2 values after prolonged wetting, and that these soils may be unstable on the AWR scales. Except for soil no. 3 (already identified by MOR1 as unstable), this group of soils all had MOR1 values <30 kPa and MOR2 values >200 kPa. Of these soils the following were not classified as unstable by AWR: Sample nos. 23, 28, 31, 32. They are however, soils known to get very hard when dry, but were previously regarded as having a stable structure. It is an illustration of how difficult interpretation of structural stability tests can be, and indicated that hardsetting possibly is not necessarily associated with structural instability. This explained an earlier finding that AWR did not correlate significantly with other parameters measured in this study. Nevertheless, as was postulated, MOR2 seemed to be a relevant measurement for the identification of possible hardsetting in the field.

Aggregate stability percentage (ASP): The measuring range for this parameter, considered as a measure of dispersion ratio, was 42,50 to 99,02% with a mean of 84,72%, a lower quartile of 78,37% and an upper quartile of 95,14% (Table 5.1; Appendix 8). This relatively narrow spread probably is the reason why ASP failed meaningful association with any other parameter measured in this study. Although the correlation coefficients of ASP with clay content ($r = 0{,}58^{**}$; with exclusion of soil 48, $r = 0{,}69^{**}$) and GDEV ($r = 0{,}52^{**}$) are statistically significant, the spread is too wide for successful identification of soil groups (plots not shown).

Aggregate stability percentage, by itself, was found to be a difficult parameter to interpret quantitatively as discussed below. Only after comparison with AWR, could it successfully be used to confirm some of the field observations. Structurally unstable soils (known from AWR-values) again grouped together based on ASP, *e.g.* the soils under flood irrigation in the semi-arid areas (Sample nos. 49, 50, 51, 57) and the low-lying hydromorphic soils (Sample nos. 3, 4, 13, 15, 16, 18, 43). On the other hand, some of the soils previously referred to as being somewhat unstable, (Fig. 5.6) were placed in the stable class (Samples 7, 8, 9). The red and yellow soils, known to be inherently stable, were grouped correctly in terms of proven stability. Subjectively, a likely threshold stability value based on this index appears to be 85%. Although Harris (1971) concluded that different soil groups, presumably due to different binding agents, cannot be compared using ASP, however, this index may serve as supporting evidence to other stability measures. It is clear that ASP, at least for the present sample population, does not relate to compactibility. Note that in this study ASP is based on determinations of the fine silt plus clay (<0,02 mm) fractions in an effort to get more sensitivity of the method with soils low in clay content.

Aggregate stability (AS): This was the most difficult structural stability measure to interpret, even when expressed as a single figure, *i.e.* mean weight diameter (MWD), and geometric mean diameter (GMD) as in Table 5.1. Not one of the different variables determined by wet sieving was meaningfully correlated with the other variables reported in this study. The data points were, for the most part, randomly scattered when plotted against several individual independent variables. Some of the best correlations of the waterstable aggregates (WSA) data were:

WSA(<0,1 mm) *versus* GDEV (<6 mm) ($r = -0{,}42^{**}$)

WSA(<0,1 mm) *versus* ASP ($r = -0{,}55^{**}$)

WSA(1,0 - 0,1 mm) *versus* ASP ($r = 0{,}50^{**}$)

Unlike the data of Alegre and Cassel (1986), no significant correlation between organic matter content and MWD or GMD was found. There also was no consistency in the stability arrangement of the soils on the basis of MWD or GMD.

Aggregate stability differed within each wet sieve class among the different soils. In some of the soil groups it seemed as if a particular size class tended to be fairly stable, *e.g.* the 0,25 to 0,1 mm class for soils 22 to 26 (red and yellow apedal horizons) and 14 to 16 (low-lying, hydromorphic soils); 2,0 to 0,5 mm class for soils 49 to 52 and 56 to 58 ( alluvial soils in the semi-arid irrigation areas); and the 0,5 to 0,1 mm class for soils 59 to 61 (yellow brown loam sands). According to Tisdall and Oades (1982) and Strickland *et al.* (1988) the aggregation and aggregation mechanisms between soil types probably differs, which explains why this measure was difficult to apply for the present study. Another possible reason why AS cannot be considered as an index of compactibility for the present sample population is presumably due to the generally low degree of aggregation of these soils compared to the results of Egashira *et al.* (1985) and that of Alegre and Cassel (1986).

The alluvial soils from the semi-arid areas, which are flood irrigated (Sample nos. 1, 41, 49, 50, 51, 52, 56, 57, 58, 64) and hydromorphic soils (Sample nos. 3, 4, 14, 15, 16, 17, 18, 48, 66) all had geometric mean diameters (GMD) lower than the median (0,59 mm) and average (0,60) values (Table 5.1; Appendix 8) due to the high percentages of aggregates in the <0,1 mm class of these soils. These were the only soils that could be grouped based on the plot of percentage of aggregates per size class, MWD or GMD *versus* textural data (plots not shown). Some of the soils considered to be very stable (*e.g.* sample nos. 44, 53, 54) also had relatively high percentages of fine aggregates. These inconsistensies with other tests of structural stability emphasised the risk of spurious conclusions based solely on the interpretation of the results of a water stable aggregates analysis.

### 5.3.5 Model validation

Generally, researchers employing regression techniques usually specify the equation to be applicable only to the data set it had been developed for. The size and nature of the present sample population created the opportunity to go one step further, namely to determine the validity of the regression equation as a model to predict MBD values for soils by applying it to samples not included in the development of the model.

First, 11 (15% of the initial population of 71) randomly selected soils were omitted in the development of the multiple regression equation. The MBD's of these 11 soils were then predicted using the regression equation and compared to the observed results. Second, this procedure was repeated for another set of nine (9) randomly selected soils and third, also for a set of five deliberately chosen "outlier" soils. The results of these three, rather strict, model validation tests are presented in Table 5.7. With the exception of the outlier group of soils, the differences between predicted and measured MBD values in Table 5.7 were quite satisfactory. The validation study illustrates the correctness of the original decision to include the whole spectrum of soil types and not to reject "outlier" soils. Alexander (1980) also held the view, that grouping of soils into subsets in order to reduce the variabilities of soil properties other than those of the independent variables will produce equations that are not good predictors for large groups of soils.

Despite the illustrated goodness of prediction by the equation, background information is required to understand why some soils were not well predicted (*i.e.* differences larger than an arbitrarily chosen 0,05 Mg $m^{-3}$ were observed). For example, soils that were not "well-predicted" by the first two validations, were: 57 (silt rich, inland alluvium); 35 (unstable, wet subsoil; AWR = 70); 69 (coarse sand); 40 (61,95% gravel); 33 (wet, clayey subsoil horizon; >29% clay) and 51 (AWR = 70). The problem of excluding "outliers" in the development of the model (soils 4, 16, 48, 57, 65) is clearly highlighted by the rather large mean difference of 0,21 Mg $m^{-3}$ between the predicted and observed values.

### 5.3.6 Prediction of field bulk density

Unlike MBD, FBD could not be predicted satisfactorily by multiple regression techniques using textural data. Even when all ten different size classes (on basis <6 mm), gravel, kurtosis and skewness were included, an $R^2$ value of 0,43 with a S.E.E. = 0,13 Mg $m^{-3}$ resulted, compared to the $R^2$ value of 0,61 and S.E.E. = 0,07 Mg $m^{-3}$ for prediction of MBD. The plot of the measured FBD versus the FBD predicted by the regression model, mentioned above, is presented in Figure 5.10. (Please note that sample nos. 40, 48 and 70 are not included because no FBD values are available for them. This could have benefited the $R^2$ value for FBD, as sample 48 was an outlier (Fig. 5.5) included in the MBD model.) In addition to the model developed for FBD being cumbersome in terms of the number of independent variables used, FBD was predicted less accurately than what MBD was predicted (compare Fig. 5.5). Furthermore, it is difficult to recognise any logical grouping of soils. It is therefore concluded that the regression technique cannot be used to successfully predict FBD for the present sample population. This is somewhat in disagreement with results of Van Wambeke (1974), who reported that the BD in the oxic horizons of soils included in his study was linearly and positively related to the percentage of sand particles (S), as follows: BD = 1,03 + 0,0045S ($r=0,73^{**}$) for the range 1,0 <BD <1,5 Mg $m^{-3}$.

## 5.4 SUMMARY AND CONCLUSIONS

A comparative study of various soil properties showed that classification of a soil in terms of compactibility clearly should consider both its textural and structural properties. The most important soil properties needed for describing compactibility and the recognition of structural instability were found to be particle size distribution, air-to-water permeability ratio and modulus of rupture. However, compaction was not necessarily associated with structural instability. This study distinguished itself from other similar studies in that a wide variety of soil types was studied instead of concentrating on a particular soil group alone. Further, the particle size distribution, represented by eleven different size fractions, improved the prediction of compactibility when expressed on a smaller than 6 mm basis as opposed to the more widely used 2 mm threshold value.

Results showed that it was possible to use a multiple regression equation based on textural data to predict Proctor maximum bulk density satisfactorily, even over a wide range of soil types. Model validation results indicated that the prediction capabilities of the suggested model might also be extrapolated to vineyard soils not included in this study. The quantification of structural stability in some cases was essential to interpret bulk density values. The use of the prediction equation, based on textural data, together with an interpretation of modulus of rupture and air-to-water permeability ratios, should considerably help in classifying soils in terms of their maximum compactibility. The results of the wet sieving analyses alone were inconclusive and the method therefore is not particularly attractive for this type of study. However, it served to illustrate the complexity of structural comparisons between soil types.

From this investigation it was inferred that no single textural or structural parameter on its own can select mutually-exclusive soil groups. Careful comparison of a number of soil properties grouped alluvial, silt rich soils from the semi-arid irrigation areas together as one group, and low- lying, hydromorphic soils as another clearly different group. It was further found that increasing silt plus clay contents tended to be associated with lower MBD's. Also, increasing kurtosis values were associated with lower MBD's. Another general outcome was that in some cases hardening upon drying was not necessarily associated with a poor soil structure and/or compactibility.

Several directions for future research are suggested by this investigation. A complete study to establish threshold values for air-to-water permeability ratios and modulus of rupture of different homogeneous vineyard soil groups should be undertaken. Methods other than regression studies should be employed to predict field bulk density from textural data. In this study it was proved that textural data do have such prediction potential, but a quantitative prediction of equilibrium field bulk density, not necessarily maximum bulk density, will be of considerable value.

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Table 5.1. Percentage of stable aggregates, mean weight diameter, geometric mean diameter, aggregate stability percentage, hydraulic conductivity and air-to-water permeability data for the experimental soils.

| Sample No. | % Stable aggregates per size class >2,0 mm | 2-1 mm | 1,0-0,5 mm | 0,5-0,25 mm | 0,25-0,1 mm | <0,1 mm | Mean weight diameter (mm) | Geometric mean diameter (mm) | Aggregate stability (%) | Air permeability ($x10^6$ $m^2$) | Water permeability ($x10^6$ $m^2$) | Hydraulic conductivity ($x10^{-4}$ cm $s^{-1}$) | Air to water permeability ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1,055 | 0,413 | 0,751 | 0,676 | 2,219 | 94,887 | 0,189 | 0,401 | 82,520 | 432,736 | 20,420 | 19,962 | 21,192 |
| 2 | 0,408 | 0,374 | 1,851 | 5,177 | 4,865 | 87,325 | 0,334 | 0,547 | 90,880 | 684,221 | 52,170 | 51,002 | 13,115 |
| 3 | 9,099 | 5,762 | 7,679 | 12,458 | 14,574 | 50,428 | 0,708 | 0,535 | 79,220 | 58,536 | 0,391 | 0,382 | 149,837 |
| 4 | 1,086 | 0,577 | 1,101 | 3,282 | 2,725 | 91,229 | 0,226 | 0,373 | 62,170 | 59,195 | 0,873 | 0,853 | 67,802 |
| 5 | 2,468 | 1,888 | 4,671 | 8,885 | 9,082 | 73,007 | 1,121 | 0,637 | 86,380 | 123,761 | 1,099 | 1,075 | 112,597 |
| 6 | 0,000 | 3,764 | 3,183 | 4,911 | 9,180 | 78,962 | 1,625 | 0,792 | 79,580 | 45,976 | 0,277 | 0,271 | 165,986 |
| 7 | 0,136 | 3,853 | 8,406 | 13,010 | 10,853 | 63,742 | 1,470 | 0,819 | 96,370 | 911,163 | 17,303 | 16,916 | 52,659 |
| 8 | 3,078 | 10,431 | 12,470 | 12,022 | 9,812 | 52,187 | 1,198 | 0,759 | 96,690 | 1662,480 | 35,965 | 35,160 | 46,225 |
| 9 | 1,946 | 9,532 | 7,054 | 1,606 | 0,167 | 79,694 | 1,033 | 0,624 | 95,970 | 276,854 | 7,505 | 7,337 | 36,890 |
| 10 | 0,000 | 0,903 | 8,179 | 0,000 | 0,000 | 90,918 | 0,798 | 0,725 | 65,420 | 454,154 | 54,592 | 53,370 | 8,319 |
| 11 | 0,094 | 4,466 | 9,360 | 0,000 | 0,000 | 86,080 | 0,833 | 0,756 | 61,320 | 669,893 | 48,641 | 47,551 | 13,772 |
| 12 | 0,000 | 0,000 | 4,964 | 5,189 | 2,743 | 87,105 | 0,905 | 0,801 | 66,230 | 1201,495 | 125,775 | 122,959 | 9,553 |
| 13 | 0,710 | 0,000 | 4,793 | 2,690 | 5,393 | 86,413 | 0,845 | 0,655 | 82,710 | 2961,309 | 0,000 | 0,000 | >4000* |
| 14 | 5,409 | 3,591 | 4,991 | 5,126 | 13,149 | 67,734 | 0,534 | 0,464 | 86,760 | 201,100 | 1,095 | 1,070 | 183,730 |
| 15 | 2,984 | 2,374 | 3,585 | 4,923 | 11,600 | 74,534 | 0,382 | 0,415 | 74,830 | 75,899 | 0,143 | 0,140 | 529,481 |
| 16 | 2,831 | 3,119 | 2,515 | 3,486 | 12,132 | 75,918 | 0,310 | 0,397 | 82,220 | 327,137 | 0,093 | 0,091 | 3512,578 |
| 17 | 0,000 | 6,109 | 1,929 | 0,667 | 6,034 | 85,260 | 0,646 | 0,495 | 76,270 | 65,258 | 0,474 | 0,463 | 137,719 |
| 18 | 0,000 | 8,982 | 0,000 | 0,411 | 0,988 | 86,619 | 0,714 | 0,529 | 65,650 | 233,644 | 0,327 | 0,320 | 713,536 |
| 19 | 0,208 | 0,560 | 6,073 | 6,735 | 0,006 | 86,417 | 0,377 | 0,579 | 85,180 | 662,964 | 24,970 | 24,411 | 26,550 |
| 20 | 0,000 | 2,145 | 1,371 | 0,000 | 0,333 | 96,151 | 0,549 | 0,617 | 65,650 | 494,563 | 26,232 | 25,644 | 18,853 |
| 21 | 10,894 | 9,904 | 10,428 | 10,752 | 4,552 | 53,470 | 0,973 | 0,688 | 95,140 | 941,452 | 11,887 | 11,621 | 79,198 |
| 22 | 0,861 | 7,204 | 12,329 | 16,426 | 12,124 | 51,055 | 0,562 | 0,586 | 97,170 | 1776,014 | 27,230 | 26,620 | 65,224 |
| 23 | 1,155 | 3,583 | 6,735 | 7,779 | 13,816 | 66,932 | 0,447 | 0,491 | 98,700 | 1207,903 | 47,662 | 46,595 | 25,343 |
| 24 | 3,428 | 3,401 | 7,342 | 8,754 | 11,890 | 65,185 | 0,733 | 0,618 | 95,180 | 2713,432 | 43,615 | 42,639 | 62,213 |
| 25 | 2,636 | 7,167 | 9,782 | 10,564 | 11,392 | 58,459 | 0,763 | 0,640 | 98,640 | 1510,840 | 55,499 | 54,256 | 27,223 |

*Real value determined = 7 548 342,7.

(continued on next page)

Table 5.1. Continued.

| Sample No. | % Stable aggregates per size class | | | | | | Mean weight diameter (mm) | Geometric mean diameter (mm) | Aggregate stability (%) | Air permeability ($x10^6$ $m^2$) | Water permeability ($x10^6$ $m^2$) | Hydraulic conductivity ($x10^{-4}$ cm $s^{-1}$) | Air to water permeability ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | >2,0 mm | 2-1 mm | 1,0-0,5 mm | 0,5-0,25 mm | 0,25-0,1 mm | <0,1 mm | | | | | | | |
| 26 | 0,000 | 2,673 | 4,540 | 10,153 | 13,093 | 69,541 | 1,420 | 0,788 | 98,390 | 1108,864 | 28,307 | 27,674 | 39,172 |
| 27 | 1,399 | 5,113 | 1,620 | 3,230 | 7,932 | 80,706 | 1,174 | 0,669 | 97,090 | 1157,868 | 48,296 | 47,215 | 23,974 |
| 28 | 0,609 | 9,914 | 10,101 | 9,204 | 4,751 | 65,420 | 1,144 | 0,765 | 94,440 | 1590,757 | 54,685 | 53,460 | 29,089 |
| 29 | 0,000 | 3,383 | 6,026 | 6,971 | 8,977 | 74,643 | 1,679 | 0,853 | 99,020 | 1936,269 | 121,002 | 118,292 | 16,002 |
| 30 | 1,336 | 2,549 | 5,117 | 6,983 | 11,181 | 72,834 | 0,896 | 0,614 | 98,510 | 2452,972 | 139,486 | 136,362 | 17,586 |
| 31 | 3,768 | 8,079 | 3,286 | 5,731 | 6,158 | 72,978 | 1,705 | 0,921 | 98,440 | 1955,517 | 40,726 | 39,814 | 48,017 |
| 32 | 3,691 | 4,614 | 3,999 | 5,187 | 8,903 | 73,607 | 1,129 | 0,686 | 94,890 | 1318,830 | 59,517 | 58,184 | 22,159 |
| 33 | 7,040 | 6,388 | 2,991 | 1,042 | 6,154 | 76,385 | 1,242 | 0,678 | 88,720 | 1386,628 | 23,264 | 22,743 | 59,605 |
| 34 | 5,967 | 0,801 | 3,425 | 7,967 | 9,506 | 72,334 | 0,628 | 0,578 | 81,390 | 963,360 | 30,893 | 30,201 | 31,184 |
| 35 | 5,722 | 2,969 | 2,247 | 1,892 | 7,438 | 79,732 | 0,647 | 0,565 | 79,300 | 1046,459 | 15,096 | 14,758 | 69,322 |
| 36 | 3,524 | 4,820 | 11,368 | 14,800 | 5,030 | 60,458 | 0,554 | 0,594 | 94,220 | 969,763 | 34,902 | 34,120 | 27,785 |
| 37 | 1,540 | 3,443 | 6,682 | 13,195 | 15,557 | 59,583 | 0,398 | 0,524 | 95,470 | 1269,312 | 40,995 | 40,077 | 30,963 |
| 38 | 6,254 | 6,561 | 11,623 | 17,203 | 7,568 | 50,790 | 0,672 | 0,626 | 97,670 | 980,566 | 37,016 | 36,187 | 26,490 |
| 39 | 10,651 | 4,112 | 5,961 | 16,253 | 10,491 | 52,533 | 0,792 | 0,636 | 96,380 | 2186,805 | 137,704 | 134,620 | 15,880 |
| 40 | 16,757 | 0,000 | 2,687 | 5,801 | 2,813 | 71,941 | 2,839 | 1,219 | 95,960 | 118,133 | 3,259 | 3,186 | 36,252 |
| 41 | 12,549 | 4,158 | 3,836 | 9,540 | 11,867 | 58,050 | 0,769 | 0,573 | 85,770 | 957,394 | 8,961 | 8,760 | 106,841 |
| 42 | 0,000 | 0,000 | 0,000 | 3,777 | 12,949 | 83,275 | 0,530 | 0,551 | 76,660 | 500,481 | 9,405 | 9,194 | 53,215 |
| 43 | 0,000 | 0,000 | 0,000 | 3,915 | 8,019 | 88,066 | 0,527 | 0,545 | 57,510 | 299,020 | 4,944 | 4,833 | 60,487 |
| 44 | 1,129 | 0,000 | 0,000 | 10.328 | 22,409 | 66,135 | 0,467 | 0,541 | 93,340 | 1244,799 | 91,807 | 89,751 | 13,559 |
| 45 | 0,000 | 0,000 | 0,000 | 2,061 | 2,783 | 95,156 | 0,476 | 0,592 | 80,380 | 611,316 | 33,308 | 32,562 | 18,354 |
| 46 | 0,000 | 2,032 | 0,000 | 1,529 | 1,041 | 95,398 | 0,658 | 0,684 | 88,380 | 716,780 | 40,648 | 39,737 | 17,634 |
| 47 | 2,019 | 2,177 | 2,325 | 3,070 | 4,784 | 85,625 | 0,637 | 0,629 | 82,560 | 1339,168 | 29,317 | 28,661 | 45,678 |
| 48 | 2,183 | 3,644 | 6,075 | 5,700 | 4,440 | 77,959 | 0,462 | 0,511 | 42,500 | 1557,089 | 18,068 | 17,663 | 86,181 |
| 49 | 9,469 | 2,241 | 2,918 | 2,535 | 0,000 | 82,837 | 0,557 | 0,442 | 75,620 | 384,706 | 2,648 | 2,589 | 145,286 |
| 50 | 10,046 | 1,556 | 3,687 | 6,322 | 4,875 | 73,514 | 0,551 | 0,429 | 80,990 | 501,673 | 2,708 | 2,647 | 185,277 |

(continued on next page)

Table 5.1. Continued.

| Sample No. | % Stable aggregates per size class >2,0 mm | 2-1 mm | 1,0-0,5 mm | 0,5-0,25 mm | 0,25-0,1 mm | <0,1 mm | Mean weight diameter (mm) | Geometric mean diameter (mm) | Aggregate stability (%) | Air permeability ($x10^6$ $m^2$) | Water permeability ($x10^6$ $m^2$) | Hydraulic conductivity ($x10^{-4}$ cm $s^{-1}$) | Air to water permeability ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 51 | 9,709 | 2,118 | 2,898 | 2,942 | 0,000 | 82,332 | 0,547 | 0,441 | 84,950 | 286,113 | 4,100 | 4,009 | 69,776 |
| 52 | 21,008 | 3,391 | 2,776 | 3,837 | 0,000 | 68,990 | 1,001 | 0,529 | 87,710 | 760,161 | 3,910 | 3,823 | 194,411 |
| 53 | 3,295 | 2,414 | 5,106 | 4,956 | 6,579 | 77,650 | 0,709 | 0,605 | 98,420 | 1149,911 | 52,936 | 51,751 | 21,722 |
| 54 | 0,567 | 1,071 | 0,000 | 6,438 | 9,957 | 81,968 | 0,506 | 0,568 | 93,550 | 1162,775 | 51,802 | 50,642 | 22,447 |
| 55 | 0,000 | 0,000 | 2,921 | 1,782 | 2,905 | 92,394 | 0,592 | 0,584 | 73,090 | 613,140 | 20,951 | 20,482 | 29,265 |
| 56 | 5,562 | 1,696 | 2,345 | 3,110 | 9,064 | 78.223 | 0,345 | 0,358 | 85,930 | 351,136 | 8,447 | 8,257 | 41,572 |
| 57 | 2,592 | 2,048 | 2,415 | 2,736 | 4,852 | 85,358 | 0,232 | 0,339 | 78,370 | 193,058 | 5,499 | 5,375 | 35,111 |
| 58 | 5,494 | 2,101 | 2,827 | 5,456 | 6,829 | 77,293 | 0,376 | 0,399 | 86,170 | 399,560 | 9,835 | 9,615 | 40,626 |
| 59 | 0,000 | 0,140 | 0,103 | 3,904 | 16,324 | 79,529 | 0,574 | 0,464 | 90,480 | 398,809 | 6,630 | 6,482 | 60,152 |
| 60 | 3,932 | 1,603 | 2,338 | 5,707 | 13,662 | 72,758 | 0,362 | 0,445 | 90,760 | 493,939 | 29,206 | 28,552 | 16,912 |
| 61 | 4,491 | 1,419 | 2,497 | 6,113 | 12,012 | 73,469 | 0,418 | 0,451 | 92,660 | 732,588 | 41,068 | 40,148 | 17,838 |
| 62 | 0,733 | 0,000 | 3,225 | 1,866 | 2,415 | 91,761 | 0,579 | 0,652 | 79,690 | 779,368 | 42,738 | 41,781 | 18,236 |
| 63 | 0,000 | 0,000 | 5,888 | 2,720 | 3,558 | 87,834 | 0,710 | 0,688 | 92,150 | 2106,081 | 135,119 | 132,093 | 15,587 |
| 64 | 2,640 | 0,230 | 0,200 | 2,178 | 1,740 | 93,011 | 0,358 | 0,500 | 76,570 | 566,786 | 14,617 | 14,289 | 38,777 |
| 65 | 4,918 | 4,272 | 9,176 | 15,621 | 3,322 | 62,691 | 0,580 | 0,552 | 86,800 | 536,982 | 16,765 | 16,390 | 32,030 |
| 66 | 0,940 | 3,303 | 0,000 | 4,075 | 6,921 | 84,761 | 0,611 | 0,592 | 69,430 | 610,361 | 7,877 | 7,701 | 77,483 |
| 67 | 26,691 | 6,509 | 0,881 | 2,489 | 2,222 | 61,207 | 1,416 | 0,757 | 90,210 | 1179,338 | 23,718 | 23,187 | 49,723 |
| 68 | 4,042 | 9,301 | 0,000 | 8,133 | 2,567 | 75,958 | 0,912 | 0,813 | 88,370 | 935,470 | 44,182 | 43,192 | 21,173 |
| 69 | 0,110 | 0,000 | 0,000 | 12,565 | 9,672 | 77,652 | 0,724 | 0,717 | 63,120 | 1134,659 | 48,871 | 47,777 | 23,217 |
| 70 | 3,643 | 1,999 | 0,000 | 5,275 | 7,357 | 81,726 | 0,571 | 0,547 | 74,410 | 129,290 | 2,814 | 2,751 | 45,952 |
| 71 | 16,633 | 4,768 | 4,000 | 9,570 | 11,276 | 53,754 | 1,107 | 0,655 | 91,810 | 1459,700 | 31,114 | 30,417 | 46,914 |

Table 5.2. Correlation matrix for selected chemical properties of 71 soil samples included in a compaction study.

| | pH | Resistance | Ca | Mg | Na | K | H | CEC | ECEC | Org. C | TH | TAl |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| pH | 1,0000* | ,7039 | ,2127 | ,6811 | ,5051 | ,5333 | -,7471 | ,7373 | ,6754 | ,1497 | ,5964 | ,6329 |
| | ,0000 | ,0000 | ,0749 | ,0000 | ,0000 | ,0000 | ,0000 | ,0000 | ,0000 | ,2126 | ,0000 | ,0000 |
| Resis- | | 1,0000 | ,0718 | ,6188 | ,7501 | ,4499 | -,4331 | ,6472 | ,3961 | ,1932 | ,5258 | ,5482 |
| tance | | ,0000 | ,5520 | ,0000 | ,0000 | ,0001 | ,0002 | ,0000 | ,0006 | ,1065 | ,0000 | ,0000 |
| Ca | | | 1,0000 | ,1565 | -,0161 | ,1103 | -,1527 | ,1437 | ,0266 | ,3889 | ,7053 | ,6932 |
| | | | ,0000 | ,1925 | ,8939 | ,3599 | ,2037 | ,2319 | ,8255 | ,0008 | ,0000 | ,0000 |
| Mg | | | | 1,0000 | ,6119 | ,4460 | -,3440 | ,8641 | ,5573 | ,1985 | ,7401 | ,7597 |
| | | | | ,0000 | ,0000 | ,0001 | ,0033 | ,0000 | ,0000 | ,0971 | ,0000 | ,0000 |
| Na | | | | | 1,0000 | ,3103 | -,2483 | ,5315 | ,2335 | ,0398 | ,4835 | ,4970 |
| | | | | | ,0000 | ,0085 | ,0368 | ,0000 | ,0500 | ,7415 | ,0000 | ,0000 |
| K | | | | | | 1,0000 | -,1594 | ,5234 | ,1175 | ,3950 | ,5981 | -,5979 |
| | | | | | | ,0000 | ,1842 | ,0000 | ,3293 | ,0007 | ,0000 | ,0000 |
| H | | | | | | | 1,0000 | -,3580 | -,5522 | ,2044 | -,5412 | -,5630 |
| | | | | | | | ,0000 | ,0022 | ,0000 | ,0872 | ,0000 | ,0000 |
| CEC | | | | | | | | 1,0000 | ,6747 | ,3159 | ,6797 | ,6962 |
| | | | | | | | | ,0000 | ,0000 | ,0000 | ,0000 | ,0000 |
| ECEC | | | | | | | | | 1,0000 | ,0743 | ,5371 | ,5561 |
| | | | | | | | | | 0000 | ,5382 | ,0000 | ,0000 |
| Org. C | | | | | | | | | | 1,0000 | ,4786 | ,4485 |
| | | | | | | | | | | ,0000 | ,0000 | ,0000 |
| TH | | | | | | | | | | | 1,0000 | ,9988 |
| | | | | | | | | | | | | ,0000 |
| TAl | | | | | | | | | | | | 1,0000 |
| | | | | | | | | | | | | ,0000 |

* Upper figures are correlation coefficients, while lower figures are significance levels.

Table 5.3. Correlation matrix for selected textural data (<6 mm basis) of 71 soil samples included in a compaction study.

| | FR16* | FR26 | FR36 | FR46 | FR56 | FR66 | FR76 | FR86 | FR96 | FR106 | GR | KUR6 | SKH6 | GDEV6 | CS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FR16* | 1,0000** | ,7264 | ,3423 | ,0314 | -,4354 | -5576 | -,5013 | -,5963 | -,4930 | -,2723 | ,3274 | ,4093 | ,3218 | ,1492 | ,8803 |
| | ,0000 | ,0000 | ,0035 | ,7950 | ,0001 | ,0000 | ,0000 | ,0000 | ,0000 | ,0216 | ,0107 | ,0004 | ,0062 | ,2144 | ,0000 |
| FR26 | | 1,0000 | ,5836 | ,2628 | -,2693 | -,4868 | -,4403 | -,5533 | -,5120 | -,4600 | -,0494 | ,6454 | ,5909 | -,2156 | ,9655 |
| | | ,0000 | ,0000 | ,0268 | ,0232 | ,0000 | ,0001 | ,0000 | ,0000 | ,0001 | ,7076 | ,0000 | ,0000 | ,0709 | ,0000 |
| FR36 | | | 1,0000 | ,8104 | ,1540 | -,4592 | -,4413 | -,5633 | -,4810 | -,4819 | -,2216 | ,5738 | ,5321 | -,3318 | ,5326 |
| | | | ,0000 | ,0000 | ,1998 | ,0001 | ,0001 | ,0000 | ,0000 | ,0000 | ,0889 | ,0000 | ,0000 | ,0047 | ,0000 |
| FR46 | | | | 1,0000 | ,3757 | -,3053 | -,3319 | -,4450 | -,3162 | -,3182 | -,2931 | ,4061 | ,3899 | -,3310 | ,1933 |
| | | | | ,0000 | ,0012 | ,0096 | ,0047 | ,0001 | ,0072 | ,0068 | ,0231 | ,0004 | ,0008 | ,0048 | ,1063 |
| FR56 | | | | | 1,0000 | ,4277 | ,1357 | -,0470 | -,0575 | -,2538 | -,4629 | ,2595 | ,3094 | -,5373 | -,3508 |
| | | | | | ,0000 | 0002 | ,2591 | ,6969 | ,6339 | ,0327 | ,0002 | ,0289 | ,0086 | ,0000 | ,0027 |
| FR66 | | | | | | 1,0000 | ,7986 | ,6577 | ,1420 | -,0533 | -,3428 | -,0361 | ,0891 | -,4148 | -,5473 |
| | | | | | | ,0000 | ,0000 | ,0000 | ,2376 | ,6588 | ,0073 | ,7649 | ,4599 | ,0003 | ,0000 |
| FR76 | | | | | | | 1,0000 | ,8451 | ,2705 | -,0546 | -2216 | -,1026 | -,0179 | -,3540 | -,4939 |
| | | | | | | | ,0000 | ,0000 | ,0225 | ,6514 | ,0889 | ,3944 | ,8825 | ,0025 | ,0000 |
| FR86 | | | | | | | | 1,0000 | ,6051 | ,1038 | -,1226 | -,3576 | -,3217 | -,2105 | -,6078 |
| | | | | | | | | ,0000 | ,0000 | ,3888 | ,3506 | ,0022 | ,0062 | ,0780 | ,0000 |
| FR96 | | | | | | | | | 1,0000 | ,2550 | -,1019 | -,4888 | -,5944 | -,0497 | -,5403 |
| | | | | | | | | | ,0000 | ,0319 | ,4384 | ,0000 | ,0000 | ,6809 | ,0000 |
| FR106 | | | | | | | | | | 1,0000 | -,0141 | -,8069 | -,8233 | ,6822 | -,4207 |
| | | | | | | | | | | ,0000 | ,9150 | ,0000 | ,0000 | ,0000 | ,0003 |
| GR | | | | | | | | | | | 1,0000 | -,1756 | -,1499 | ,5934 | ,0881 |
| | | | | | | | | | | | ,0000 | ,1795 | ,2531 | ,0000 | ,5032 |
| KUR 6 | | | | | | | | | | | | 1,000 | ,9267 | -,6400 | ,6006 |
| | | | | | | | | | | | | ,0000 | ,0000 | ,0000 | ,0000 |
| SKH6 | | | | | | | | | | | | | 1,0000 | -,6152 | ,5298 |
| | | | | | | | | | | | | | ,0000 | ,0000 | ,0000 |
| GDEV6 | | | | | | | | | | | | | | 1,0000 | -,0924 |
| | | | | | | | | | | | | | | ,0000 | ,4437 |
| CS | | | | | | | | | | | | | | | 1,0000 |
| | | | | | | | | | | | | | | | ,0000 |

* FR16 = 2,00-1,00 mm ⎫ Coarse sand
FR26 = 1,00-0,50 mm ⎭
FR36 = 0,50-0,30 mm ⎫ Medium sand
FR46 = 0,30-0,25 mm ⎭
FR56 = 0,25 - 0,106 mm —— Fine sand

FR66 = 0,106-0,075 mm ⎫ Very fine sand
FR76 = 0,075-0,053 mm ⎭
FR86 = 0,053-0,020 mm —— Coarse silt
FR96 = 0,020-0,002 mm —— Fine silt
FR106 = <0,002 mm —— Clay

GR = 6,00-2,00 mm
KUR6 = Kurtosis
SKH6 = Skewness
GDEV6 = Geometric mean deviation
CS = 2,00-0,05 mm

**Upper figures are correlation coefficients, while lower figures are significance levels.

Table 5.4. Model fitting results for the prediction of maximum bulk density from textural data, showing different variable selection (backward) options:

a) Final model with minimum variables and maximum $R^2_{adj.}$;

| Independent variable | Coefficient | Std. error | t-value | Sig. level |
|---|---|---|---|---|
| Constant | 2,065138 | 0,044657 | 46,2444 | 0,0000 |
| FR26 (1,00 to 0,50 mm) | 0,004437 | 0,001053 | 4,2138 | 0,0001 |
| FR36 (0,50 to 0,30 mm) | 0,004099 | 0,001652 | 2,4818 | 0,0157 |
| FR106 (<0,002 mm) | -0,008325 | 0,001433 | -5,8100 | 0,0000 |
| KURTOSIS 6 | -0,041223 | 0,006086 | -6,7733 | 0,0000 |
| GRAVEL (6,00 to 2,00 mm) | 0,003587 | 0,000737 | 4,8691 | 0,0000 |

$R^2$ = 0,6124 M.A.E. = 0,0463 Durb.Wat. = 1,911
$R^2_{adj.}$ = 0,5825 S.E.E. = 0,0663

b) Variables FR16 and FR46 forced into the model;

| Independent variable | Coefficient | Std. error | t-value | Sig. level |
|---|---|---|---|---|
| Constant | 2,066833 | 0,045142 | 45,7855 | 0,0000 |
| FR16 (2,00 to 1,00 mm) | 0,000778 | 0,002237 | 0,3477 | 0,7293 |
| FR26 (1,00 to 0,50 mm) | 0,003718 | 0,001465 | 2,5370 | 0,0137 |
| FR36 (<0,50 to 0,30 mm) | 0,005861 | 0,002914 | 2,0114 | 0,0486 |
| FR46 (0,30 to 0,25 mm) | -0,004474 | 0,006156 | -0,7267 | 0,4701 |
| FR106 (<0,002 mm) | -0,008244 | 0,001472 | -5,6003 | 0,0000 |
| KURTOSIS 6 | -0,040672 | 0,006244 | -6,5143 | 0,0000 |
| GRAVEL (6,00 to 2,00 mm) | -0,003384 | 0,000818 | 4,1374 | 0,0001 |

$R^2$ = 0,6170 M.A.E. = 0,0454 Durb.Wat. = 1,860
$R^2_{adj.}$ = 0,5744 S.E.E. = 0,0670

c) FR16 + FR26 (coarse sand), and FR36 + FR46 (medium sand) added up.

| Independent variable | Coefficient | Std. error | t-value | Sig. level |
|---|---|---|---|---|
| Constant | 2,067153 | 0,045183 | 45,7505 | 0,0000 |
| Coarse sand (2,00 to 0,50 mm) | 0,003131 | 0,000686 | 4,5661 | 0,0000 |
| Medium sand (0,50 to 0,25 mm) | 0,002855 | 0,001169 | 2,4415 | 0,0174 |
| FR106 (<0,002 mm) | -0,008612 | 0,001451 | -5,9334 | 0,0000 |
| KURTOSIS 6 | -0,041305 | 0,006173 | -6,6912 | 0,0000 |
| GRAVEL (6,00 to 2,00 mm) | 0,003158 | 0,000767 | 4,1147 | 0,0001 |

$R^2$ = 0,6033 M.A.E. = 0,0465 Durb.Wat. = 1,914
$R^2_{adj.}$ = 0,5728 S.E.E. = 0,0671

M.A.E. = Mean absolute error.
S.E.E. = Standard error of estimate.
Durb.-Wat. = Durbin-Watson summary statistic.

Table 5.5. Correlation matrices for the coefficient estimates of different regression models for the prediction of maximum bulk density:

a) <u>for model in Table 5.4a</u>;

| | Constant | FR26* | FR36 | FR106 | KUR6 | GR |
|---|---|---|---|---|---|---|
| Constant | 1,0000 | ,2229 | -,2841 | -,9226 | -,7894 | -,3898 |
| FR26* | | 1,0000 | -,3662 | -,1808 | -,4465 | -,1311 |
| FR36 | | | 1,0000 | ,1318 | -,0947 | ,2058 |
| FR106 | | | | 1,0000 | ,7403 | ,2165 |
| KUR6 | | | | | 1,0000 | ,2384 |
| GR | | | | | | 1,0000 |

b) <u>for model in Table 5.4b;</u>

| | Constant | FR16 | FR26 | FR36 | FR46 | FR106 | GR | KUR6 |
|---|---|---|---|---|---|---|---|---|
| Constant | 1,0000 | ,0366 | ,1289 | -,1417 | -,0243 | -,9066 | -,3728 | -,7748 |
| FR16 | | 1,0000 | -,5870 | -,1239 | ,1729 | -,1349 | -,3917 | -,0926 |
| FR26 | | | 1,0000 | -,3705 | ,2522 | -,0953 | ,1937 | -,3186 |
| FR36 | | | | 1,0000 | -,8198 | ,1936 | ,0422 | ,0803 |
| FR46 | | | | | 1,0000 | -,1483 | ,0701 | -,1645 |
| FR106 | | | | | | 1,0000 | ,2286 | ,7476 |
| GR | | | | | | | 1,0000 | ,2285 |
| KUR6 | | | | | | | | 1,0000 |

c) <u>for model in Table 5.4c</u>.

| | Constant | CS6 | MS6 | FR106 | KUR6 | GR |
|---|---|---|---|---|---|---|
| Constant | 1,0000 | ,2004 | -,2804 | -,9186 | -,7790 | -,4114 |
| CS6 | | 1,0000 | -,2406 | -,1912 | -,4622 | -,2449 |
| MS6 | | | 1,0000 | ,1056 | -,1392 | ,2538 |
| FR106 | | | | 1,0000 | ,7489 | ,2346 |
| KUR6 | | | | | 1,0000 | ,2811 |
| GR | | | | | | 1,0000 |

*FR16 = 2,00 to 1,00 mm fraction <6 mm basis.
FR26 = 1,00 to 0,50 mm fraction <6 mm basis.
FR36 = 0,50 to 0,30 mm fraction <6 mm basis.
FR46 = 0,30 to 0,25 mm fraction <6 mm basis.
FR106 = <0,002 mm fraction <6 mm basis.
GR = Gravel = 6,00 to 2,00 mm.
KUR6 = Coefficient of kurtosis (<6 mm basis).

Table 5.6. Model fitting (final backwards selection) results for modulus of rupture on soil textural (<2 mm basis) and CEC data of 71 soil samples used for compaction studies.

a) MOR1 (after 1 hour);

| Independent variable | Coefficient | Std. error | t-value | Sig. level |
|---|---|---|---|---|
| Constant | -6,3939 | 6,1317 | -1,0428 | 0,3009 |
| FR8 | -2,2827 | 0,7344 | -3,1082 | 0,0028 |
| FR9 | 4,0025 | 0,4684 | 8,5453 | 0,0000 |
| FR10 | -0,2797 | 0,2452 | -1,1411 | 0,2580 |
| CEC | 5,4798 | 1,6470 | 3,3274 | 0,0014 |

$R^2$ = 0,6161 M.A.E. = 13,2239 Durb-Wat. = 1,570
$R^2$adjusted = 0,5929 S.E.E. = 21,1203

b) MOR2 (after 12 hours).

| Independent variable | Coefficient | Std. error | t-value | Sig. level |
|---|---|---|---|---|
| Constant | -11,2754 | 18,9030 | -0,5965 | 0,5529 |
| FR6 | -2,0841 | 1,4508 | -1,4366 | 0,1556 |
| FR9 | 7,1657 | 1,1466 | 6,2494 | 0,0000 |
| FR10 | 2,0473 | 0,7064 | 2,8984 | 0,0051 |
| CEC | 21,7455 | 4,5690 | 4,7594 | 0,0000 |

$R^2$ = 0,6949 M.A.E. = 43,8010 Durb.-Wat. = 1,612
$R^2$ = 0,6764 S.E.E. = 59,9512

M.A.E. = Mean absolute error.
S.E.E. = Standard error of estimate.
Durb.-Wat. = Durbin-Watson summary statistic.

Table 5.7. Results of a model validation technique done by predicting Proctor maximum bulk densities (MBD) of soils not included in the development of the regression model used to predict MBD.

| Series No. | Sample No. | Maximum bulk density (Mg $m^{-3}$) Measured | Predicted* | Difference | Brief soil description (Appendices 1 and 3; Table 4.1) |
|---|---|---|---|---|---|
| 1 | 7 | 1,9471 | 1,9571 | +0,0100 | coarse clay loam; 27,3% gravel. |
| 2 | 13 | 1,8950 | 1,9435 | +0,0485 | wet coarse sand clay loam; 26,2% clay. |
| 3 | 22 | 1,7950 | 1,7665 | -0,0285 | fine sand clay; 34,7% clay. |
| 4 | 29 | 1,9300 | 1,9462 | +0,0162 | coarse sand clay; 24,2% clay. |
| 5 | 32 | 1,8938 | 1,8952 | +0,0014 | wet coarse sand clay loam; 27,8% clay. |
| 6 | 33 | 1,8250 | 1,8778 | +0,0528 | wet coarse sand clay; 29,2% clay. |
| 7 | 40 | 2,0750 | 2,0054 | -0,0696 | fine sand clay; 61,95% gravel; 14,32% clay. |
| 8 | 51 | 1,7850 | 1,8369 | +0,0519 | 0% gravel; 26,6% silt; 13,4% clay. |
| 9 | 57 | 1,6875 | 1,7932 | +0,1057 | 0% gravel; 54,2% fine sand; 35,7% clay. |
| 10 | 60 | 1,7900 | 1,8097 | +0,0197 | fine sand loam; 67,93% fine sand. |
| 11 | 69 | 1,9250 | 1,8481 | -0,0769 | coarse sand; 2,5% gravel; 4,4% clay. |
| $\lvert\bar{x}_{1-11}\rvert$ | - | - | - | 0,0437 | |
| 12 | 11 | 1,9281 | 1,8898 | -0,0383 | coarse sand; 4,5% gravel; 2,4% clay. |
| 13 | 22 | 1,7950 | 1,7661 | -0,0289 | as above. |
| 14 | 26 | 2,0063 | 1,9805 | -0,0258 | coarse sand clay loam; 34,3% gravel. |
| 15 | 28 | 1,9750 | 1,9276 | -0,0474 | coarse sand clay loam; 15,6% gravel. |
| 16 | 35 | 2,0226 | 1,9384 | -0,0842 | wet, medium sand loam; 10% clay. |
| 17 | 42 | 1,9878 | 1,9716 | -0,0162 | medium loam sand; 5,6% clay. |
| 18 | 45 | 1,7620 | 1,7887 | +0,0267 | coarse sand; 1,6% gravel; 2,4% clay. |
| 19 | 54 | 1,9400 | 1,9192 | -0,0208 | coarse sand loam; 2,3% gravel; 15,9% clay. |
| 20 | 70 | 1,9444 | 1,9614 | +0,0170 | coarse sand; 1,5% gravel; 8,4% clay. |
| $\lvert\bar{x}_{12-20}\rvert$ | - | - | - | 0,0305 | |
| 21 | 4 | 1,9750 | 1,8954 | -0,0796 | wet, fine sand loam; 1% gravel; 8,4% clay. |
| 22 | 16 | 1,9917 | 1,9058 | -0,0859 | wet, loam; 18,59% clay. |
| 23 | 48 | 1,6000 | 2,1595 | +0,5595 | coarse sand clay loam; 1% gravel; 27,7% clay. |
| 24 | 57 | 1,6875 | 1,7932 | +0,1057 | as above. |
| 25 | 65 | 1,6844 | 1,8936 | +0,2092 | wet fine sand loam; 2,3% gravel; 15,4% clay. |
| $\lvert\bar{x}_{21-25}\rvert$ | - | - | - | 0,2080 | |

*Prediction equations:

a) Series: 1 to 11

MBD(Mg $m^{-3}$) = 0,003360(Gravel) + 0,003864(FR26**) + 0,003830(FR36) - 0,008801(FR106) - 0,042045(Kurtosis) + 2,087338

$R^2$ = 0,5375 $R^2_{adjusted}$ = 0,5764 n = 60

S.E.E. = 0,0699 M.A.E. = 0,00477

b) Series: 12 to 20

MBD(Mg $m^{-3}$) = 0,00355(Gravel) + 0,00433(FR26) + 0,00388(FR36) - 0,00814(FR106) - 0,03977(Kurtosis) + 2,056963

$R^2$ = 0,5791 $R^2_{adjusted}$ = 0,5415 n = 62

S.E.E. = 0,0698 M.A.E. = 0,04855

c) Series: 21 to 25

MBD(Mg $m^{-3}$) = 0,00324(Gravel) + 0,00423(FR26) + 0,00439(FR36) - 0,00789(FR106) - 0,04081(Kurtosis) + 2,063078

$R^2$ = 0,7224 $R^2_{adjusted}$ = 0,6993 n = 65

S.E.E. = 0,0503 M.A.E. = 0,0381

**FR26 = % of 1,00 to 0,50 mm fraction of coarse sand.
FR36 = % of 0,500 to 0,300 mm fraction of medium sand.
FR106 = % of clay (<0,002 mm).
S.E.E = Standard error of estimate.
M.A.E = Mean absolute error.

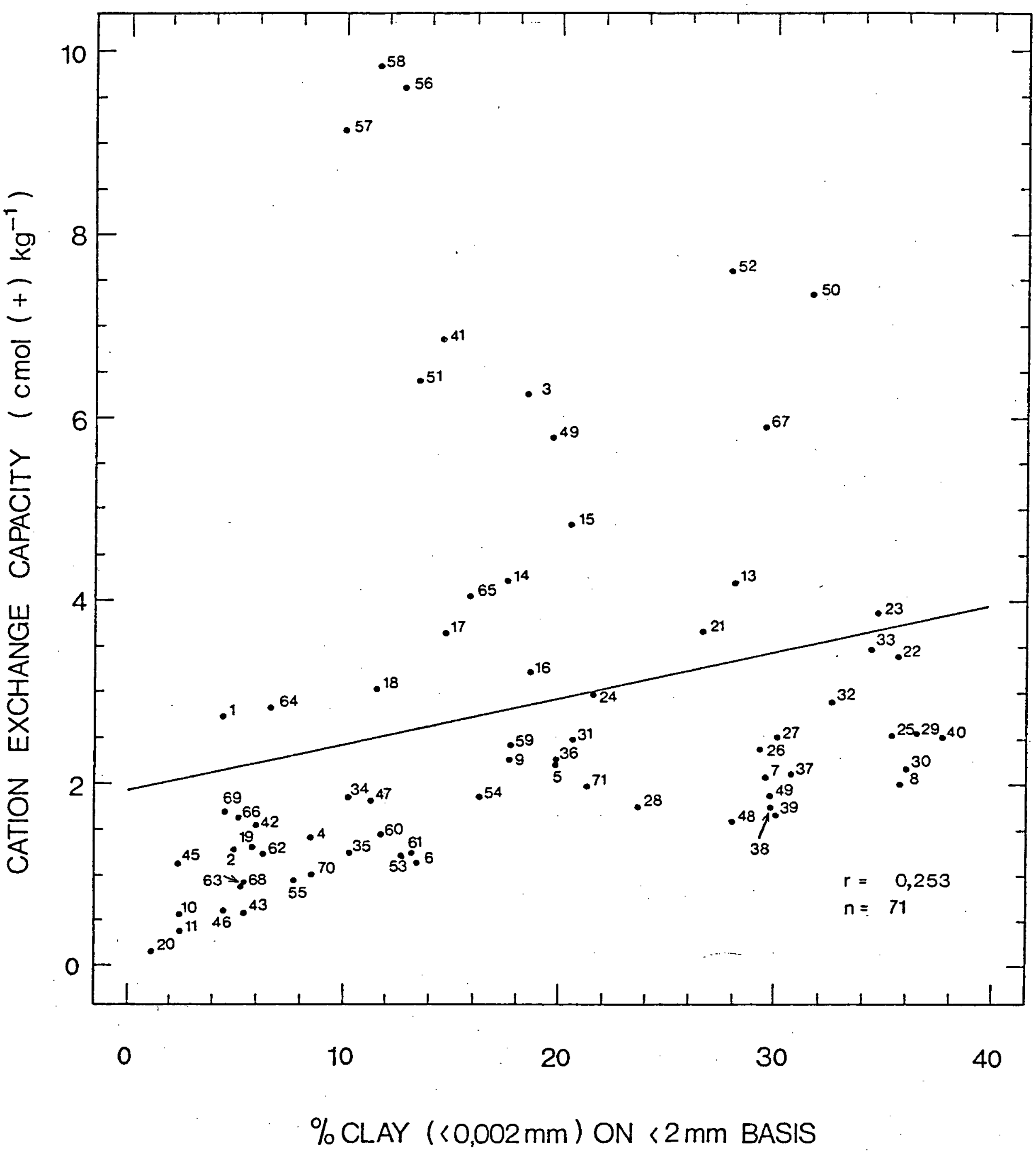


Fig. 5.1. Relationship between cation exchange capacity and clay content of 71 soil samples from various locations in the viticultural areas.

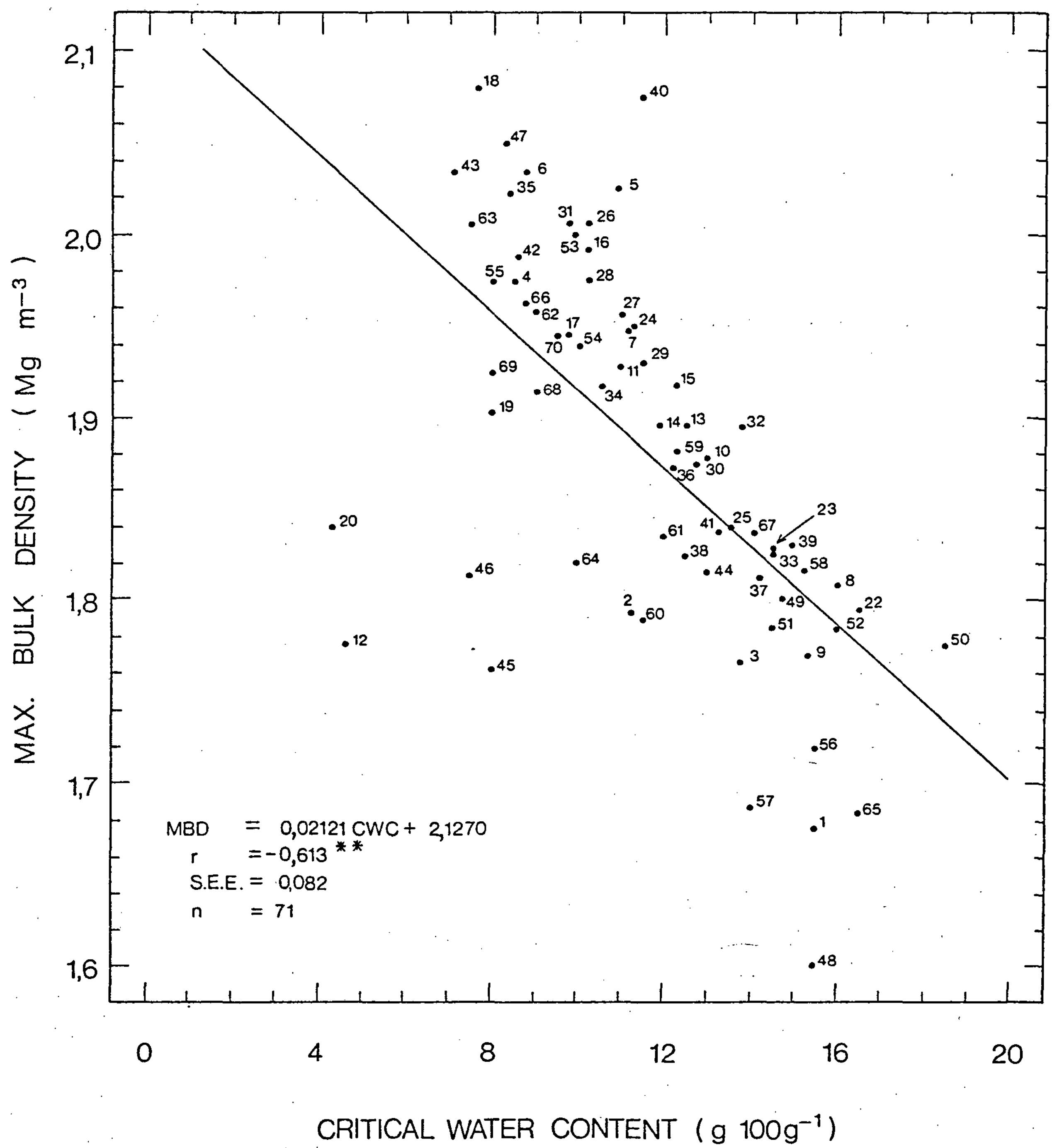


Fig. 5.2. Relationship between Proctor maximum bulk density and critical water content as determined for 71 soil samples from various locations in the viticultural areas.

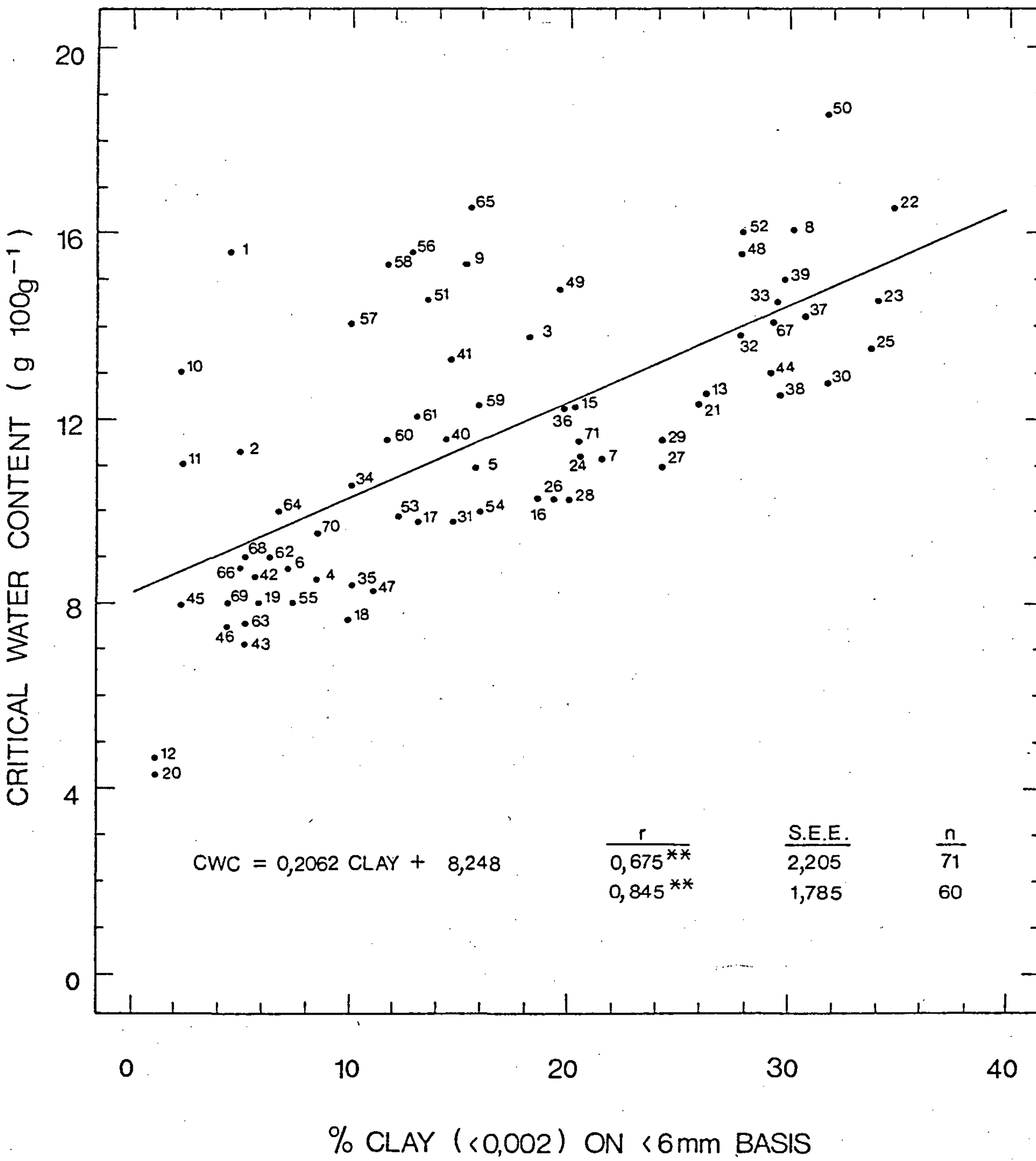


Fig. 5.3. Relationship between clay content and the critical water content of 71 soil samples from various locations in the viticultural areas, and which had been studied for compactibility.

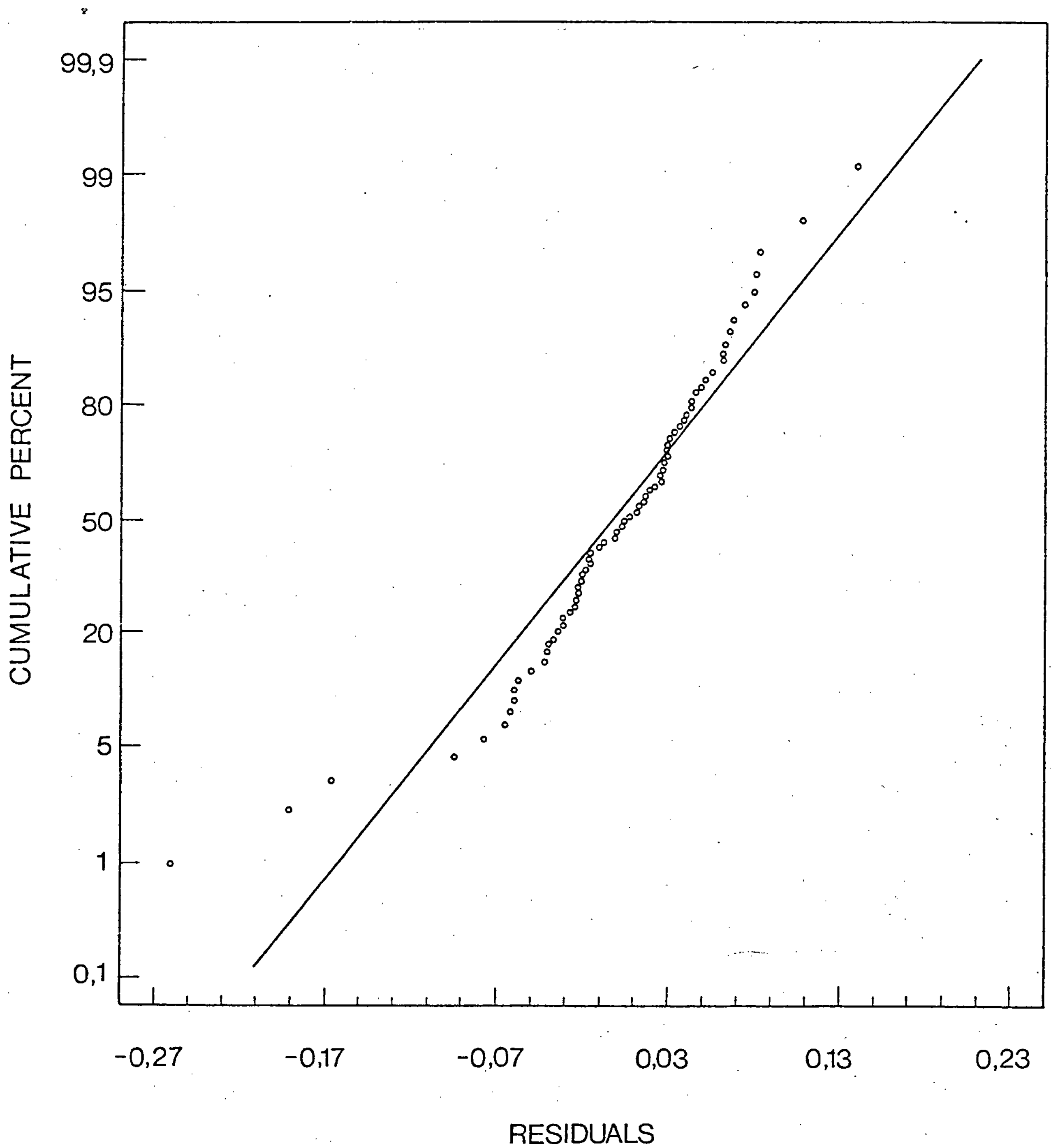


Fig. 5.4. Normal probability plot of the residuals of the prediction model for maximum bulk density from textural data. Model presented in Table 5.4a.

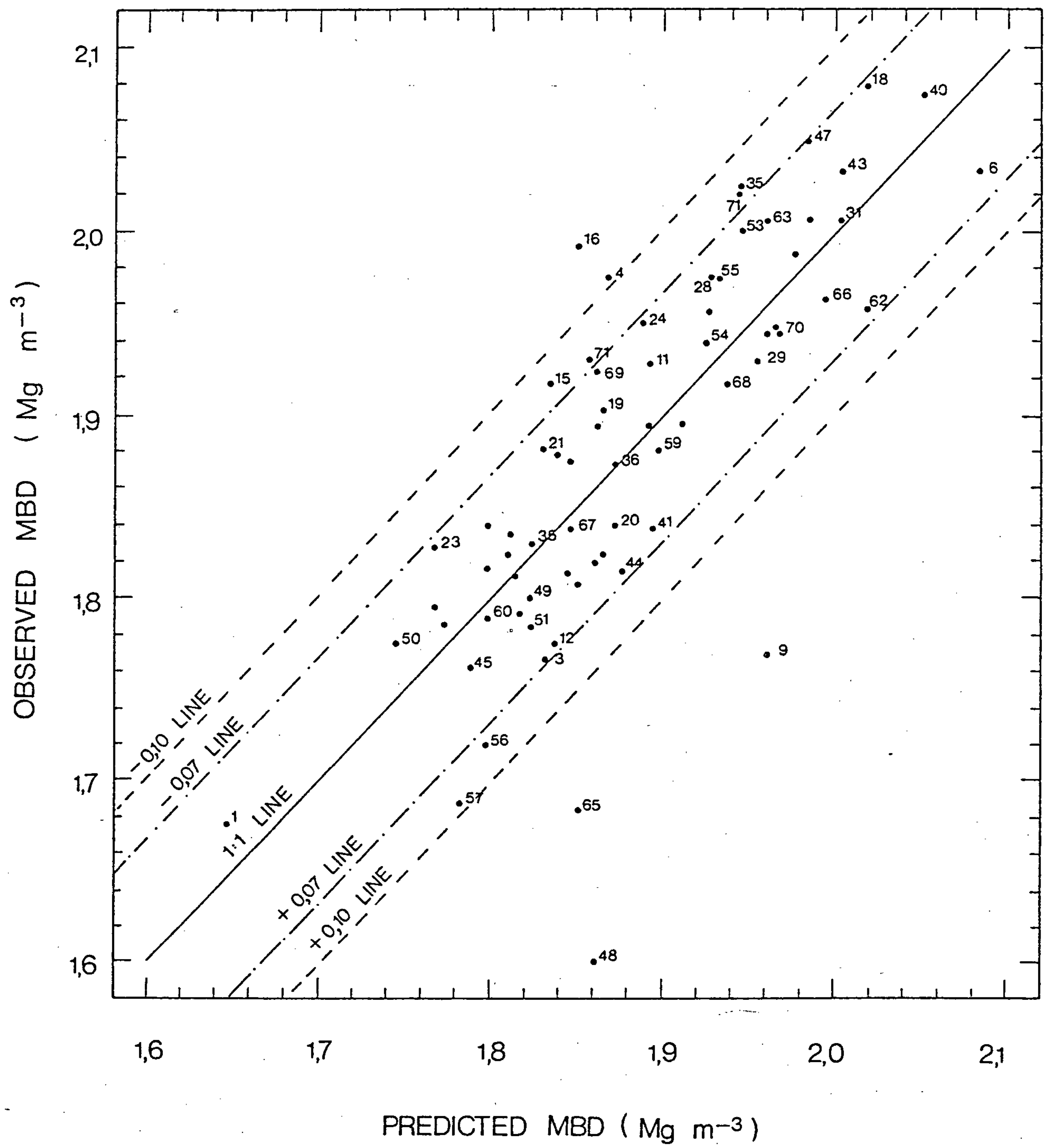


Fig. 5.5. Comparison between Proctor maximum bulk densities and maximum bulk densities predicted by the model in Table 5.4a for 71 soils from various locations in the viticultural areas.

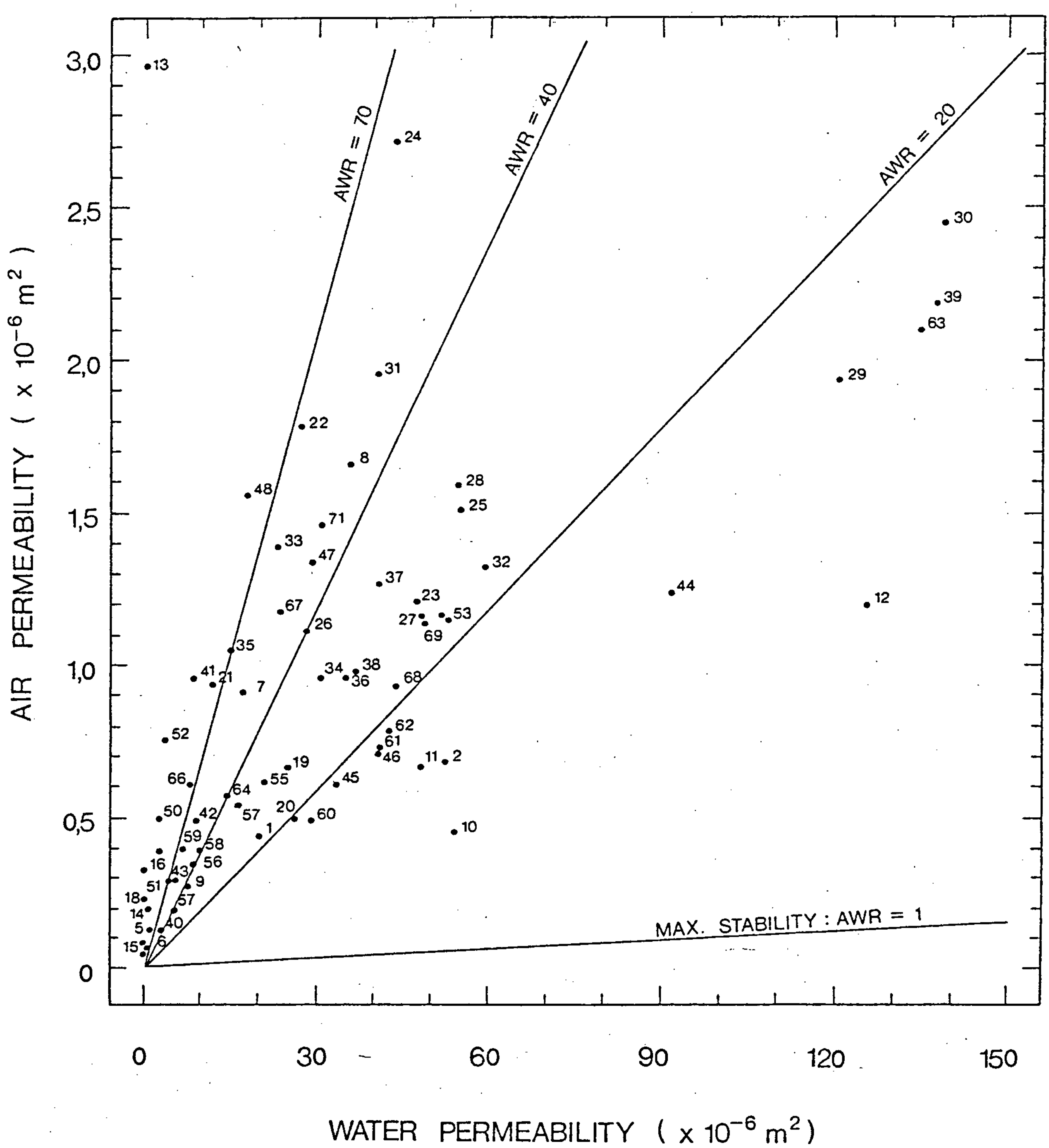


Fig. 5.6. Air-to-water permeability ratios as depicted by air and water permeability values for 71 different soils from various locations in the viticultural areas.

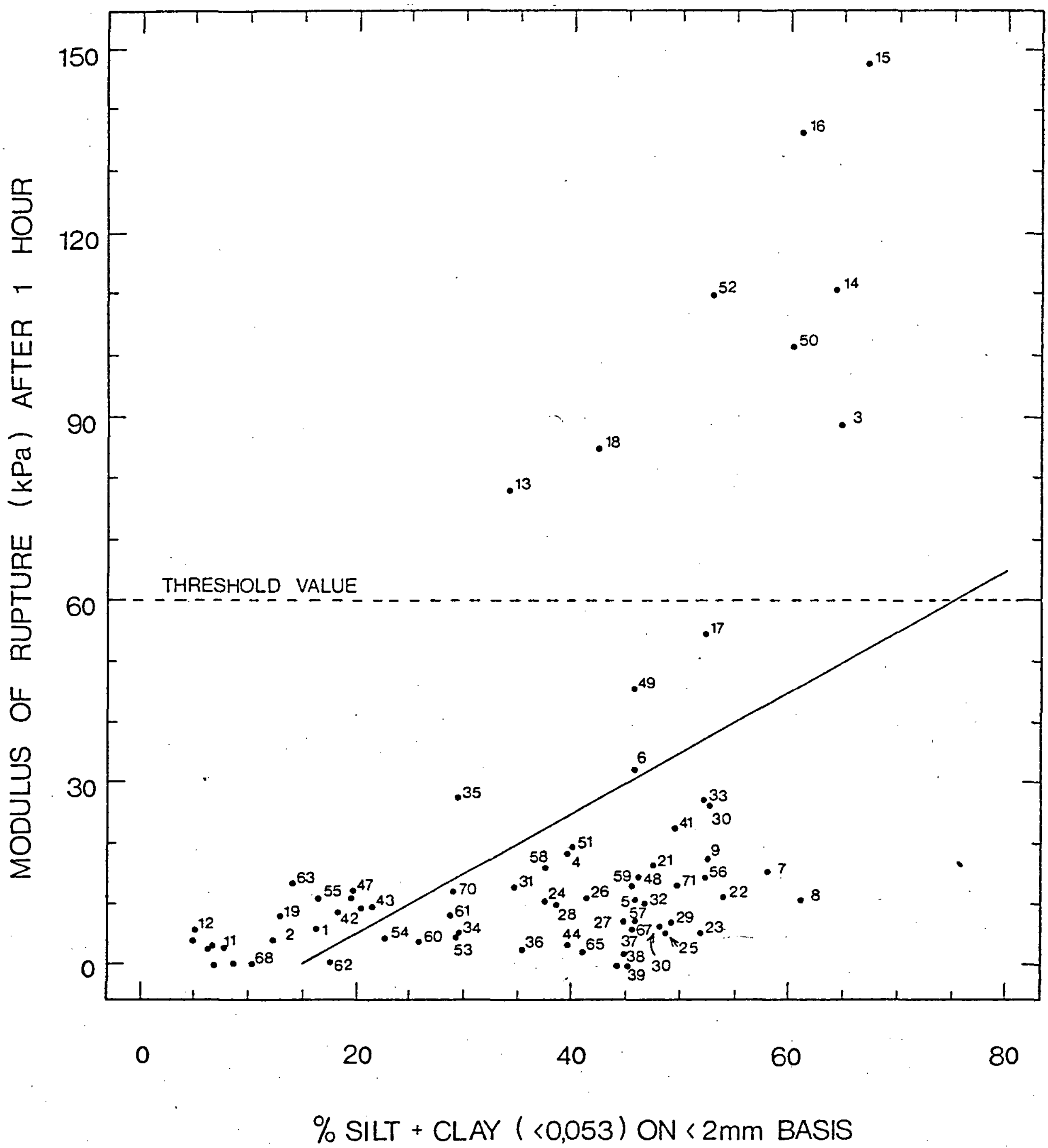


Fig. 5.7. Relationship between modulus of rupture (1 hour soaking time) and silt plus clay content for 71 different viticultural soils used in a compaction study.

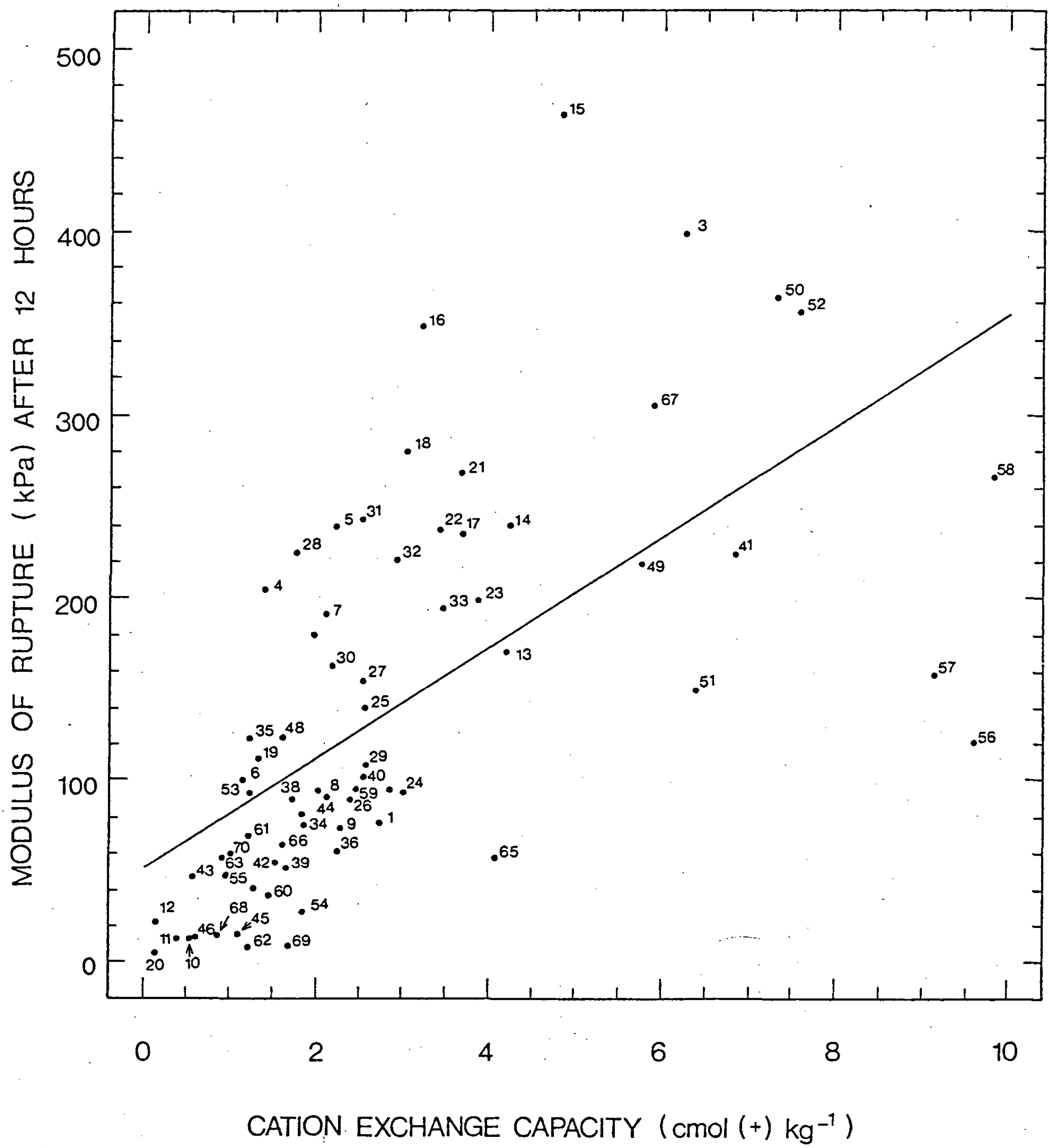


Fig. 5.8. Relationship between modulus of rupture (12 hours soaking time) and cation exchange capacity for 71 different viticultural soils used in a compaction study.

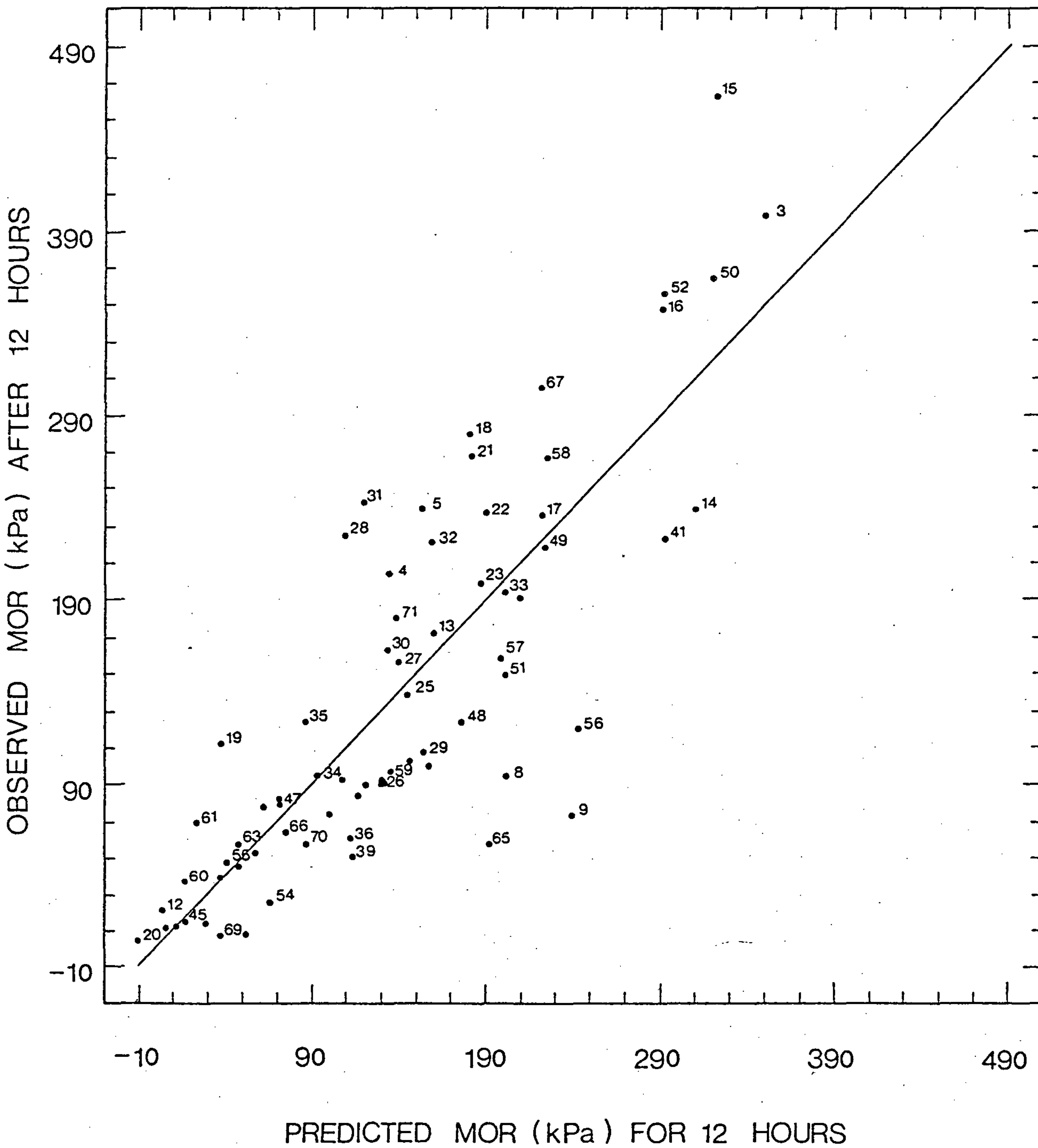


Fig. 5.9. Relationship between modulus of rupture after twelve hours soaking time and modulus of rupture predicted by the model in Table 5.6b for 71 soils from various locations in the viticultural areas.

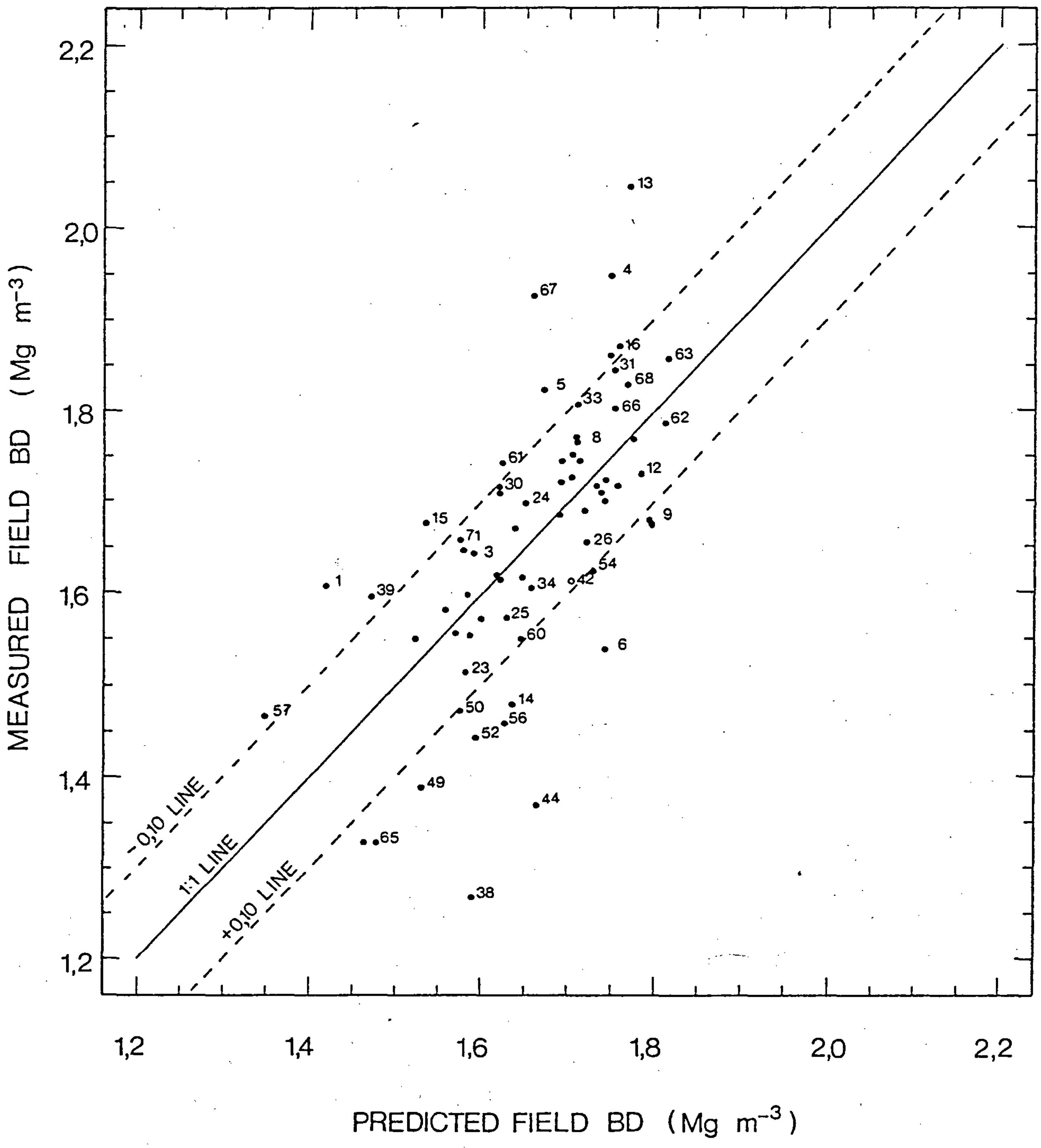


Fig 5.10. Comparison between measured field bulk density and predicted field bulk density using a multiple regression model using soil textural data of 71 soils from various locations in the viticultural areas.

# CHAPTER 6

# APPLICABILITY OF A COMPUTER MODEL TO PREDICT SOIL BULK DENSITY FROM TEXTURAL DATA

## ABSTRACT

The permanence of expensive soil loosening actions is uncertain on at least some soil types because a measure of the equilibrium bulk density to which the soil will settle is not available on a routine basis. Seventy-one soil samples comprising of a wide textural range and different susceptibilities to compaction were collected. The Gupta-Larson random packing model was tested for its ability to predict soil bulk density (BD) from textural data. The model overpredicts Proctor maximum bulk density (MBD) but yields reasonable predictions for measured field bulk density (FBD) for the majority of soils. Soils of which the predicted random BD differed by more than the standard error of estimate (S.E.E. = 0,08 Mg $m^{-3}$) from the ideal 1:1 line sorted into logical groups according to common soil properties or soil conditions. This fact implies that the origin and most prominent morphological properties of the soil must be known before the meaning of the predicted BD can be interpreted. It was verified that gravel (2-6 mm $\phi$) should be included as an extra size class and that the particle size data should be corrected for gravel content. Average particle densities, or even the universally accepted value of 2,65 Mg $m^{-3}$, can be used for the different size fractions. The model is sensitive to changes in the BD's of the size fractions. In order to reduce the input data requirement of the model, it is suggested that using an average BD for the size fractions of a homogeneous soil group be investigated. Experience gained with the model makes it possible to determine beforehand on a routine basis where and when compaction might occur in vineyard soils.

## 6.1 INTRODUCTION

Impeded root growth due to soil compaction has been adequately demonstrated in the different grapevine growing areas of the Republic of South Africa (Van Huyssteen, 1983; Chapter 4 of this dissertation). Further, it is often found that soils which had been deep ploughed at great expenses to as deep as 100 cm, recompact unexpectedly to even higher densities than before loosening. Such recompaction is typically observed upon drying out of the soil after intensive wetting due to either winter rainfall or heavy irrigations. Other soils are more stable and compact only under compression forces like implement traffic. Because of variations in soil type, this different sensitivities to recompaction might occur over relatively short distances or even at different depths within the same profile.

This phenomenon of varying sensitivity to recompaction makes decision-making on soil management very difficult, and there is a definite need for some basis of assessing potential compaction problems beforehand in order to determine the permanence of loosening actions. Only then a correct decision on whether or not to deep plough a new land can be taken. Surface management strategies, *e.g.* minimum *versus* conventional tillage practices, can also be based on the equilibrium BD to which the soil will settle. According to Panayiotopoulos and Mullins (1985), the equilibrium BD to which a cultivated soil will settle determines its land use capability. To summarise, management of soil compaction requires a knowledge of when and where compaction might occur.

Measurement of compaction in the field is a cumbersome task because mechanical impedance and BD exhibit both spatial and temporal variability (Cassel, 1982). Although penetrometer soil strength (PSS) can be rapidly and easily obtained (Van Huyssteen, 1983), BD is easier than PSS for diagnosing compaction from a procedural standpoint (Vepraskas, 1988). Further, PSS varies with soil texture, soil water content, penetrometer type and rate of penetration (Cassel, 1982; Bradford, 1986), which all complicate the interpretation of penetrometer data. Recently, Gupta and Allmaras (1987) stated that there is a scarcity of reliable information concerning soil compaction in the field that can be related either theoretically or statistically to laboratory measurements of soil compaction.

In a previous study (Chapter 5) a fairly good relationship between Proctor MBD and soil texture was found by using a multiple regression technique. Unfortunately, the same was not found for FBD. Maximum BD is the maximum compaction attained under an applied load and, although it is useful for classifying soils according to potential compactibility, it does not necessarily relate to equilibrium FBD. Thus, a technique to predict FBD is still lacking.

The efforts and difficulties involved in using particle size distribution of a soil in order to determine compactibility have abundantly been reported in the literature (Westman and Hugill, 1932; White and Walton, 1937; Bodman and Constantin, 1965; Van der Watt, 1969; Gupta and Larson, 1979; Moolman, 1981; Panayiotopoulos and Mullins, 1985). When particle size analyses are done, weight frequencies are used to represent particle frequencies; a factor which, when not taken in account, may cause some statistical and interpretation problems with, for instance, regression analysis. According to Wyrwoll and Smyth (1985), the sampling variability of the observed mass-size distribution cannot be calculated since the size of individual grains is not independent, and the nature of their dependence is not known.

Moss (1972), as quoted by Wyrwoll and Smyth (1985), pointed out that sieving sorts the soil particles by shape as well as by size. According to the latter authors, Moss found that highly flattened quartz particles came to rest up to four sieves above highly elongated ones of the same size. Wyrwoll and Smyth (1985) therefore concluded that extremes of a grain-size distribution are as much of an artefact of the particle size analysis technique as it may be a physical entity of the soil investigated. It must also be kept in mind that the basis for particle size analysis is the assumption that the soil particles are spheres (Jumikis, 1962). Despite these shortcomings of textural data, in this study it was decided to continue investigating soil texture as a determinant of BD because soil texture is one of the more permanent characteristics of a soil (Soil Survey Staff, 1975). Further, observations in the field plus evidence from the literature quoted above, point to a relationship between soil texture and compaction.

As discussed in Chapter 1, packing is the mutual arrangement of the soil particles within the mass of soil. According to Jumikis (1962), density is one of the soil properties that will be influenced by packing arrangements. The purpose of the present study was to test the applicability of an existing packing model of Gupta and Larson (1979) to describe soil compaction of vineyard soils. Because of the shortcomings of particle size analysis data discussed above, and also because there might be other soil properties not considered by the model, and which may directly or indirectly contribute to soil compaction, it was hypothesised that the model would not be able to predict FBD with the same accuracy for all vineyard soils. It was postulated that the identification of outlier soils, *i.e.* soils of which the observed FBD are clearly under- or overpredicted by the model, could be an advantage in itself in that soil groups with different compactibility potentials and compaction mechanisms could be identified. It was hoped that results of the model would complement the regression technique (Chapter 5) which was used to predict MBD.

## 6.2 MATERIALS AND METHODS

The soils and the analytical methods are the same as those described in Chapter 4 and of which different properties are compared in Chapter 5. The background and origin of the 71 soils are listed in Appendix 1, while selected morphological soil properties are given in Table 4.1.

The random packing model described by Gupta and Larson (1979), briefly outlined in Chapter 1, was used to predict maximum potential compaction and random BD, the latter being considered to represent the equilibrium FBD. The textural data in Appendices 2 and 3 were used as primary input to the packing model. The particle fractions were not adjusted to sum up to 100% because no fraction was determined by difference. In order to stick to routine particle size determinations, the cumulative totals of the fractions were required to be between 97 and 104%. The mass percentage of particles in each fraction was expressed both on a <2 mm (Appendix 2) and a <6 mm (Appendix 3) basis. Predictions of BD's of soils and glass bead systems gave variable results and were successful only when the mixtures consisted of particles that had severalfold differences in their diameter (Bodman and Constantin, 1965; Staple, 1975). In contrast, the model described by Gupta and Larson (1979) had no limitation on the ratio of particle diameters or on the number of components. In order to accommocate soils with long tails of particle size distribution, it was decided for the present study to use at least ten different particle size classes <2 mm plus a 2 to 6 mm size class for gravel. The 11 size classes of the different fractions entered into the model were: 6,00 to 2,00 mm; 2,00 to 1,00 mm; 1,00 to 0,50 mm; 0,50 to 0,30 mm; 0,30 to 0,25 mm; 0,25 to 0,106 mm; 0,106 to 0,075 mm; 0,075 to 0,053 mm; 0,053 to 0,020 mm; 0,020 to 0,002 mm and <0,002 mm.

Further inputs to the model were the particle densities (Appendix 6) and packing BD's (Appendix 7) for each size fraction as determined for each individual soil. The BD's of the 0,02 to 0,002 mm and <0,002 mm fractions could not be determined, because not enough of these fractions were available, and were selected as 1,30 and 1,20 Mg $m^{-3}$ after Gupta and Larson (1979). In addition, the model was also run using BD's of 1,10; 1,20; 1,40 and 1,50 Mg $m^{-3}$ for the fine silt fraction (0,020-0,002 mm) and BD's of 1,00; 1,10; 1,30; 1,40 and 1,50 Mg $m^{-3}$ for the clay fraction (<0,002 mm). The particle density of the <0,002 mm fraction could also not be determined, because it was a problem to get enough sample from this fraction and also this fraction swelled upon wetting, and the mean particle density of the 0,05 to 0,02 mm and 0,02 to 0,002 mm fractions of the 71 samples was thus used to represent the particle density (PD) of the <0,002 mm fraction (Mean PD = 2,7094 Mg $m^{-3}$). The model was used to predict the following BD's: minimum soil BD's, random BD's and maximum BD's with cavity radii (Fig. 1.2) of 0,225R; 0,155R; 0,732R; 0,531R; 0,285R and 0,414R; where the decimal figures represent the void size ratio and R is the average equivalent radius per size fraction. Predicted minimum and random BD's were corrected for percentage organic matter content using the formula of Adams (1973) as suggested by Gupta and Larson (1979).

The various predicted BD's were compared with FBD as well as with Proctor MBD using simple regression analysis and X-Y scatterplots. The means, which describe position, and standard deviations, which describe scale, of the observed and predicted values were used for further model evaluation (Willmott, 1984). In addition, the index of agreement (d), suggested by Willmott (1984), was used to evaluate the predictive ability of the model. This value, d, is considered a descriptive relative error measure that reflects the overall relative degree to which the observed value (O) is approached by a predicted value (P). The index of agreement varies between 0,0 (complete disagreement) and 1,0 (perfect agreement). The index of agreement was calculated as follows:

Root mean square error (RMSE) = $[1/N \sum_{i=1}^{n} (P_i - O_i)^2]^{0,5}$, and

Potential error variance (PE) = $(|P_i - \bar{O}| + |O_i - \bar{O}|)^2$,

where N = number of samples

P = predicted value, and

$\bar{O}$ = observed mean value.

$$\text{Index of agreement (d)} = 1 - \frac{N(\text{RMSE})^2}{\text{PE}}$$

The textural data of Moolman (1981) was also used as input to the packing model in an attempt to further verify the model for South African conditions. Extrapolation from the present data yielded the following bulk- and particle densities for the different size fractions used by Moolman (1981).

| Fraction (mm) | Bulk density (Mg $m^{-3}$) | Particle density (Mg $m^{-3}$) |
|---|---|---|
| 2,000 to 1,000 | 1,455 | 2,65 |
| 1,000 to 0,500 | 1,458 | 2,65 |
| 0,500 to 0,250 | 1,453 | 2,65 |
| 0,250 to 0,125 | 1,433 | 2,65 |
| 0,125 to 0,063 | 1,440 | 2,66 |
| 0,063 to 0,031 | 1,336 | 2,67 |
| 0,031 to 0,016 | 1,336 | 2,67 |
| 0,016 to 0,008 | 1,336 | 2,75 |
| 0,008 to 0,004 | 1,300 | 2,75 |
| 0,004 to 0,002 | 1,300 | 2,75 |
| <0,002 | 1,200 | 2,75 |

The hypothesis that the ratio,

$$P = \frac{\text{Predicted maximum BD}}{\text{Predicted random BD}},$$

might give an indication of surface sealing and pan formation (Gupta and Larson, 1979) was also tested.

## 6.3 RESULTS AND DISCUSSION

The relationship between Proctor maximum bulk density (MBD) and field bulk density (FBD) is depicted in Fig. 6.1. The poor correlation coefficient ($r = 0{,}54^{**}$; S.E.E. = 0,08 Mg $m^{-3}$) illustrates the wide scatter around the fitted line. Exclusion of the recently loosened soils from the data set did not improve the correlation coefficient much ($r = 0{,}56^{**}$, S.E.E. = 0,09 Mg $m^{-3}$). These soils (nos. 14, 38, 44, 49, 51, 65) had relative compaction values of less than 80% (Table 4.3) and were not at an equilibrium FBD. The rest of the soils in the sample population was considered to be at an equilibrium FBD. The following soils have MBD's of only 0,10 Mg $m^{-3}$ higher than their FBD, and thus lie near to the 1:1 line (indicating that they occur near their maximum compactibility in the field): No. 1 (loamy fine sand, which is a plough pan typically formed under clean tillage and flood irrigation on the alluvial soils of the semi-arid irrigation areas); No. 4 (fine sandy loam, naturally dense B21 horizon of a hydromorphic Westleigh soil); No. 8 (clay loam, naturally dense B22 horizon of a granitic Glenrosa); No. 9 (loam, naturally dense weathering C horizon); No. 12 (coarse sand, E horizon of Longlands); No. 33 (sandy clay, B21 horizon of Longlands with slight clay illuviation); No. 61 (fine sandy loam, probably natural density enhanced by tillage); No. 68 (coarse sand, plough pan). Soil nos. 13 and 67 had FBD's even higher than their MBD's. Soil no. 13 is a sandy clay loam, B21 horizon of a Longlands into which clay illuviation took place, while soil no 67 is a sandy clay loam topsoil of a Katspruit which is subjected to waterlogging and gets very hard upon drying. The results in Figure 6.1 indicate that MBD does not relate in a logical way to equilibrium FBD. It is, however, possible that simultaneous prediction of FBD and MBD might complement each other by defining the range of BD's that could be expected to occur in a specific soil.

Several possible variations in input data to the Gupta-Larson model are possible and different BD's can be predicted. Table 6.1 shows the comparison between observed Proctor MBD and the maximum, random and minimum BD's predicted from the model. In this specific model the textural data expressed on a <6 mm basis were used, *i.e.* percentage gravel (6,0-2,0 mm) was also included (Appendix 3). Also, measured particle (Appendix 6) and bulk densities (Appendix 7) were used for the different size fractions. Fine silt (0,020-0,002 mm) and clay (<0,002 mm) BD's of 1,30 and 1,20 Mg $m^{-3}$, respectively, were used. In comparison with the 1:1 line the data show that the packing model is unable to predict Proctor MBD of the present sample population.

The relation between the predicted BD's and MBD for some packing arrangements is given in Figure. 6.2. Because the graphs were plotted on a 1:1 scale, point size clouding to the left of Figures 6.2a and b and to the right of Figures 6.2c and d, makes the fitted lines look strange at first sight. The theoretical MBD predicted by the packing model grossly overestimated Proctor MBD as determined in this study, which in turn was much higher than FBD. Gupta and Larson (1979) pointed out that the predicted MBD is different for each soil and is dependent on particle size distribution, and densities of the component fractions. Sample nos. 49 (Fig. 6.2a), 55, 65 and 70 (Fig. 6.2b) had relatively high percentages of fine fractions (Appendix 3) with high particle densities (Appendix 6), which might explain the particularly high predicted MBD's for them. Furthermore, the particle size distribution (Appendix 4) might be of such nature that all of the finer particles fit into the voids of coarser fractions at a specific packing arrangement and do no contribute to the bulk volume (Gupta and Larson, 1979). This may be the reason why sample nos. 13, 34, 4, 35, 18 (Fig 6.2a) and sample nos. 10, 11, 66, 26, 43 (Fig. 6.2b) could be packed to such high theoretical MBD's of >2,60 Mg $m^{-3}$. This filling of pores with finer particles by the model is probably also the reason for the intercepts of the fitted lines for MBD being >0 (Table 6.1, Fig. 6.2a and b), because natural soils always have some open pores, even in the densest state. The best correlation between measured and predicted MBD's was obtained when the soil particles were packed according to a dense tetragonal (0,285R) arrangement (Table 6.1 and Fig. 6.2b). The similarity of the slopes of the regression lines and the 1:1 lines in Fig. 6.2a and 6.2b are noteworthy, which except for the tetragonal packing with 0,155R, is not the case for the other packing arrangements (Table 6.1).

Both random and minimum BD's as predicted by the model underestimated the MBD's, which is to be expected (Fig. 6.2c and 6.2d). The extent to which predicted minimum BD approaches the BD's of the loose soils is shown below (note that soil no. 14 was loosened two years prior to sampling and was not trafficked ever since):

| Soil no. | Field BD (Mg $m^{-3}$) | Minimum BD (Mg $m^{-3}$) |
|---|---|---|
| 14 | 1,48 | 1,27 |
| 38 | 1,27 | 1,33 |
| 44 | 1,37 | 1,34 |
| 49 | 1,39 | 1,28 |
| 51 | 1,33 | 1,30 |
| 65 | 1,33 | 1,36 |

Attention is drawn to the definite higher predicted minimum BD's for the sandy soils indicated in Fig. 6.2d, and to the lower minimum BD's of some of the silt rich soils (*e.g.* nos.3, 7, 8, 9, 41, 47, 59, 65). The sandy soils have high kurtosis values (>8), while the silt rich soils have kurtosis values of <4 (Appendix 9). The correlation coefficient (r) for the regression of minimum BD on kurtosis is 0,745** with S.E.E. = 0,048 Mg $m^{-3}$. This is a clear demonstration that the theshold BD value of a soil is specific to that soil, *i.e.* silt rich soils have minimum BD's roundabout 1,24 Mg $m^{-3}$, while the corresponding value for sandy soils is 1,46 Mg $m^{-3}$ although both groups are at their loosest possible state. These observations confirmed the well-known fact that the same BD value for texturally different soils has different meanings (Archer and Smith, 1972; Vepraskas, 1988). Daddow and Warrington (1983) reported that critical BD's decrease with increasing silt or clay, while increasing sand content increase critical BD's. To this regard the model may be useful to sort soils into BD-classes based on textural composition which in turn can help to see measured FBD in a better perspective.

It should be kept in mind that in this study Proctor MBD was determined on the total soil mass that passes through a 6 mm sieve. The undisturbed, natural aggregates so included might be one of the reasons why the soils could not be compacted to the high theoretical MBD's predicted with the Gupta-Larson model. The packing model uses clay-size particles to fill empty pores while clay in the field has a definite aggregating effect which is not accounted for by the model. Only subsoil horizons into which clay illuviation have taken place (*e.g.* nos. 8, 13 and 16) might display such high densities in the field. Nevertheless, the high predicted MBD's point to the potentially high BD's that may be encountered on some vineyard soils when mismanaged.

Variations in the input data, *e.g.* texture on <2 mm basis, exclusion of gravel, on average particle and bulk densities did not yield better prediction of MBD and are not reported here. The rest of the discussion will therefore concentrate on random predicted BD.

Quantitative measures to compare the ability of the random packing model to predict FBD from different input data are summarised in Table 6.2. The following conclusions can be drawn from this data:

* When model nos. 1, 2, 3 and 4 are compared on the basis of their d-values, and the averages for the predicted BD's, it is clear that gravel (6-2 mm) must be included in the input data in order to get a better prediction of FBD. Higher average predicted BD's and higher standard deviations are obtained when gravel is included in the input data. The standard deviations are, however, lower than those of the field data.

* Because of the similarity of the measures of model performance, there is not much

difference in the prediction ability of the model when using textural data either <2 mm (model no. 2) or <6 mm (model no. 4).

* The model gives good results (d >0,64) both when average particle densities from Appendix 6 (model no. 7) and an overall average particle density of 2,65 Mg m$^{-3}$ (model no. 9) are being used. The former model is only slightly better than the latter.

* The model is sensitive to the BD's of the individual fractions, and a poorer prediction (d = 0,59) of FBD is obtained when average BD's from Appendix 7 (model no. 8) instead of the measured BD's are being used.

Plots of predicted random BD *versus* FBD for selected input data are presented in Figure. 6.3, which illustrates these points graphically.

Since the BD's of the fine silt and clay fractions were assumed to be 1,30 and and 1,20 Mg m$^{-3}$, respectively, sensitivity studies were performed (Table 6.2) to study their influence on both predicted maximum and random BD's. The statistical measures reported in Table 6.2 failed to point out a critical BD for any of these two fractions when compared for the sample population as a whole. The effect of varying the BD of these two fractions was further investigated on all the soils. From Table 6.3, presenting a few selected soils, it is clear that the predicted MBD of soils with less than *ca.* 18% fine silt (<6 mm basis) did not increase with increasing BD of this fraction. Only seven soils in the present study contained more than 18% fine silt with the highest fine silt content being 29,31% for soil no. 16. All of these seven soils showed an increasing predicted MBD when the BD of the fine silt fraction increases. The predicted random BD was affected in very much the same way as MBD when the BD of fine silt increased. Like for MBD, it was also found that only soils with more than *ca.* 18% fine silt packed to higher random BD's when the BD of the fine silt fraction increased. For soils with less than 18% fine silt the effect of varying fine silt BD's on predicted random BD's was not as stable as it was for the predicted MBD's. However, no pattern emerged. Allowing for the stability of the model to predict random BD, and for practical purposes, the predicted random BD's of soils with less than 18% fine silt could be considered constant over the range of fine silt BD's tested.

The effect of increasing the BD of the clay fraction on predicted BD is illustrated in Table 6.4. Other than for fine silt, the effect of clay BD on predicted MBD was erratic and one half of the soils reported showed increasing MBD with increasing clay BD, while the other half was not affected. Only at clay contents lower than approximately 10% (<6 mm basis) did the MBD remain constant with increasing clay BD. Predicted random BD increases with increasing clay BD and, other than for MBD, this effect was noticeable even to the lowest clay contents. The order of magnitude of the changes in predicted

BD's due to changes in the BD's of the fine silt and clay fractions for the most soils were within acceptable limits ( 0,08 Mg $m^{-3}$) compared to the S.E.E. for the predictions of random BD (Table 6.2). The results were also within the limits of accuracy to which FBD can be measured (Cassel, 1982). Although Gupta and Larson (1979) had a smaller database than the present study, they also reported that the effect of varying BD of the finest fractions varied with soil type and that in general MBD was more sensitive than random BD. For the present study, however, it seemed that random BD was more sensitive than MBD. The results of the reported sensitivity analysis are complex and need further investigation. It was therefore decided not to calibrate the model for either fine silt or clay BD. In contrast to this decision, Warrington and Daddow (1981) found it necessary to modify the model to increase the clay BD's of their samples with increasing clay content up to a maximum clay BD of 1,60 Mg $m^{-3}$ in order to get realistic predictions of FBD. It is, however, not clear from their report for what range of clay contents the model was used, although it was mentioned that the model underpredicted BD for horizons composed of >50% smectite clays.

In the light of the above evaluation of input data to the model, it was decided to accept a BD of 1,30 Mg $m^{-3}$ for fine silt and a BD value of 1,20 Mg $m^{-3}$ for the clay fraction and to use the results of model no. 4 in Table 6.2 as the basis for further discussion. The textural input data used in this model were considered to be realistic representations of the samples, and thus field conditions, and as such are best suitable to predict FBD. The relationship between random BD, as predicted by model no. 4, and FBD is given in Figure 6.4. The results of the linear correlation between the two variables showed an $R^2$ value of 22,5%, S.E.E. of 0,078 Mg $m^{-3}$, a slope 0,276 and an intercept of 1,195 Mg $m^{-3}$. As stated earlier, the slope should be 1,0 and the intercept should be 0,0 in the case of a perfect match. According to Willmott (1984) the intercept describes additive error and slope describes proportionality error.However, the correlation between FBD and predicted random BD, as described by Pearson's r, is insufficient as a quantitative measure to evaluate model performance because at first sight it might appear as if there is not much association between FBD and random BD. Willmott (1984) warned that correlation coefficients may be misleading measures of model performance. The discrepancy between the predicted line and the best fit 1:1 line can best be explained when a 1:1 line and two boundary lines, at $\pm$0,08 Mg $m^{-3}$ (= S.E.E.) distance from the 1:1 line, are fitted to the data in Figure. 6.4. The "outlier" values with respect to the 0,08 Mg $m^{-3}$ boundaries on the 1:1 line could be related to definite soil properties/conditions at the time of sampling.

For ease of interpretation the "outlier" soils in Figure 6.4 are listed in Table 6.5. The FBD of soils that were cultivated regularly, and thus not long ago before sampling (Soil nos. 38, 44, 49, 51), were overpredicted by random BD (RBD) and it might be an indication that these soils will in time settle to the predicted BD's. Sample no. 65 (not an outlier) were loosened and ridged three months previous to sampling. When this sandy loam soil was irrigated afterwards, it settled to almost the predicted BD of 1,37 Mg $m^{-3}$. Soils 14 (FBD = 1,48 *vs.* RBD = 1,65 Mg $m^{-3}$), 15 (FBD = 1,68 *vs.* RBD = 1,65 Mg $m^{-3}$)

and 17 (FBD = 1,62 *vs.* RBD = 1,66 Mg $m^{-3}$) were also loosened and ridged, but two years prior to sampling. Although all three these soils (nos. 14, 15, 17) tend to form a surface crust, it was observed that they do not recompact deeper down in the ridges, and stay loose as was predicted, provided that they are not subjected to wheel compaction. More examples of topsoils that settle to almost the predicted FBD over longer periods after loosening are: Soil nos. 6, 10, 19, 41, 56 and 60. The FBD's of some of the undisturbed, naturally dense red and yellow subsoil horizons (nos. 22, 23, 25, 26, 27, 39) were overpredicted by random BD. These soils are known to be well drained in the natural state, but once they have been loosened some of these soils might recompact to very high densities especially under implement and wheel traffic.

Some of the soils (nos. 4, 47, 59, 61, 62, 63, 68, 69) with a total sand content of more than approximately 60% (<2 mm basis) had higher FBD's than were predicted by the model. The reason why the two coarse sands, 68 and 69, do not group with the other coarse sands (nos. 10, 11, 12, 20, 45, 46), which were well predicted, is not clear, especially when their kurtosis values of >8,6 in Appendix 9 and the particle size distribution curves in Appendix 4 are considered. The rest of the underpredicted group (nos.4, 47, 59, 61, 62, 63) had kurtosis values of less than 5,8. It must be kept in mind that these two groups of soils were also grouped separately in Figure 5.2 on the basis of their critical water contents and MBD's. Another group of soils (nos. 3, 21, 31, 67) of which the FBD was underpredicted included topsoils that displayed hardsetting characteristics as confirmed by high modulus of rupture values after 12 hours soaking time. The three subsoils (nos. 8, 13, 16) into which clay illuviation occurred also had higher FBD's than predicted by the model. This is ascribed to an ongoing filling of pores with clay particles - a process not simulated by the random packing part of the model. They were, however, still by far overpredicted by the tetragonal packing, which simulates filling of pores by fine particles, as illustrated in Figure 6.2b. The soils from the semi-arid areas (nos. 41, 49, 50, 51, 52, 56, 57, 58), which were already recognised as a separate group in Chapter 5, again grouped together to the lower left side of Figure 6.4. Further, it appears as if the FBD's of sample nos. 4, 61 and 68, which were underpredicted, approach their MBD-values (Fig. 6.1) due to intensive tillage practices on these soils. This observation illustrates the point made earlier, namely that there is a need for the prediction of both FBD and MBD.

For the correct interpretation of the random BD predicted by the model, it is necessary to understand why the FBD of some soils cannot be accurately predicted. That is the reason for all the emphasis laid on the "outlier" soils in the discussion above. It is, however, as a matter of perspective, necessary to point out that the FBD of the majority of soils included in this study (43 out of 68) was well-predicted by the model, *i.e.* within the limits of the $\pm$0,08 Mg $m^{-3}$ boundaries on the 1:1 line. These soils represent a wide textural distribution and include different soil types. It is concluded that the equilibrium FBD of these soils are primarily determined by their particle size distribution characteristics. In addition, it may be accepted that the FBD of the deliberately chosen loose soils (Nos. 14, 38, 44, 49, 51) will eventually settle to the predicted random BD.

The results of the predicted MBD's from textural data of Moolman (1981) are given in Figure 6.5. Judged on correlation coefficients alone the best result was obtained with a stable pyramidal packing ($r = 0{,}680^{**}$) of the soil particles as presented in Figure 6.5a. The stable tetrahedral packing (Fig. 6.5c) had a slope of 1,062, but as can be seen from the intercept of 0,255 this packing arrangement overpredicted all the measured Proctor MBD's. Soils most probably differ in their packing arrangements of particles at maximum compaction. For instance, the fitted line for the present data has a slope of *ca*. 1 when packed according to a pyramidal/tetrahedral arrangement with a cavity size of 0,225R (Fig. 6.2a), which is not the case for the soils that Moolman (1981) investigated (Fig. 6.5a). The fitted line for the latter soils has a slope of *ca*. 1,0 with a tetrahedral packing arrangement with cavity size 0,414R (Fig. 6.5c), while the corresponding slope for the soils of the present study is 2,11 (Table 6.1). The reason(s) for this difference in "preference" packing arrangements are not clear.

As could be expected, the random arrangement of individual particles, meant to represent FBD underpredicted the MBD's (Fig. 6.5d). Eventhough extrapolated values were used for the particle and bulk densities of individual fractions, it is interesting to note how the pyramidal (Fig. 6.5a) and tetragonal (Fig. 6.5b) packing arangements separated out the major soil groups included in the Moolman data, while the tetrahedral packing arrangement (Fig. 6.5c) apparently did not result in such grouping. In the random packing arrangement (Fig. 6.5d) the soils also tended to separate into groups.

One clearly identifiable group, which for the most part was underpredicted, is the artificial soil mixtures, numbered 20 to 29 in Figure 6.5, made up from fine sand, silt and clay separates from an Oakleaf soil from Riversdal in the Southern Cape. The fine sand contents of these soils decreased in 5% increments from 94,0% (no. 20) to 50% (no. 29) while the clay contents increased in increments of 1,2% from 1,2% (no. 20) to 12% (no. 29). The silt contents increased gradually from 3,8% (no. 20) to 37,5% (no. 29). The other soil type of which members clearly grouped together, by being overpredicted, was a Westleigh soil (nos. 4 to 9 in Fig. 6.5a and b) from Stellenbosch which is regarded as a hydromorphic soil type. Sample nos. 6 and 9, which did not group with the other samples of the Westleigh, contained markedly less fine sand than the rest, *viz.* 9,3% less than the 45% of no. 5, the next nearest sample in the group. The characteristics of the model confirmed by this additional exercise are that for the most part the model overpredicts Proctor MBD, and that it separates soil groups on basis of their textural characteristics. Moolman (1981) used the kneading type Proctor test while the falling hammer method was used for the present study.

Plots of the P-values suggested by Gupta and Larson (1979) *versus* modulus of rupture (MOR2) and FBD are presented in Figure 6.6. Higher P-values are indicative of a wider particle size distribution. The

P-values reported here were calculated by dividing the predicted MBD's at a cavity size of 0,414R by the random BD not corrected for organic matter content. It is difficult to interpret these plots of MOR2 and FBD against P, as no threshold value for P is known. Suffice to point out that the topsoils (Sample nos. 3, 14, 17, 21, 41, 49, 67), which are known to have water infiltration problems in the field, and which get hard on drying, are grouped in the upper righthand side of Figure 6.6a with P-values >1,4 and MOR2-values >200 kPa. Except for soil no. 58 (4,2), all the mentioned soils had kurtosis values of less than 2,7 (on a <6 mm basis in Appendix 9).

The grouping of some soils, nos. 14, 41, 50, 52, 56, 57 and 58, to the right of Figure 6.6b might be indicative of a sensitivity to pan formation and/or slumping upon wetting. In practice these soils are known to exhibit a tendency towards pan formation. A plot of Proctor MBD *versus* P did not explain more about the nature of P (not shown). In general, it is concluded that the P-value is not very successful in classifying the soils included in the present study for pan formation or for crusting.

## 6.4 SUMMARY AND CONCLUSIONS

In order to make the correct soil management decisions before the vineyard, a long-term crop, is being established the sensitivity of South African vineyard soils to compaction should first be assessed. For this purpose a stochastic random packing model developed by Gupta and Larson (1979) was used to predict BD. Use of the model allows soil textural information to be employed in assessing soil BD in a way which would otherwise be difficult in field and laboratory experimentation.

Although, with the present study, the predicted minimum BD was found to be unrealistically low, it is argued that these BD's can be used as a first approximation to identify soils with different packing characteristics due to their textural composition. In general, the model predicts higher minimum BD's for sandy soils as a group and lower minimum BD's for the group of silt rich soils. The predictions of BD must be understood in terms of critical BD's in order to prevent misinterpretations of the predicted values. The model provides partial insight in some important soil properties associated with compaction in the field in that it sorts soils of which the BD was poorly predicted into logic groups based on common soil properties.

The 2 to 6 mm particle size class should be included as input to the model in order to predict equilibrium FBD more accurately. Average particle densities for the different size fractions, or even the generally accepted 2,65 Mg $m^{-3}$, can be used without influencing the prediction results. The model is, however, sensitive to changes in the BD of size fractions, but it may be possible to use average BD's for the fractions of a homogeneous soil group, *e.g.* for the alluvial soils from the semi-arid areas. This will make the model more economical in terms of analyses required in the laboratory. However, this will have to be investigated further. For strongly aggregated soils, aggregate size distribution in addition to particle size distribution may be required for improved predictions. This was beyond the scope of this study as such soils seldom compact spontaneously.

In conclusion, the model makes it possible to establish a better connection between soil texture and BD. The packing model is a useful tool for the prediction of equilibrium FBD's. The information presented here proves that despite the shortcomings of particle size data it may be used on a routine basis as an indicator of where (in the profile, or in the field), when and to what extent soil compaction might occur. The packing model should be used in conjunction with the regression model proposed to predict MBD.

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Table 6.1. Comparison of observed Proctor maximum bulk density (MBD) against maximum, random and minimum bulk densities (BD) predicted by the Gupta-Larson model[a)] for 71 soils used in a compaction study.

| Predicted BD at different packing arrangements[b)] | Slope | Intercept ($Mg\ m^{-3}$) | Coefficient of determination ($R^2$ in %) | Std. error of estimate ($Mg\ m^{-3}$) | Probability level |
|---|---|---|---|---|---|
| MBD: pyramidal/tetrahedral (0,225R) | 0,9065 | 0,5543 | 13,60 | 0,2363 | 0,0016 |
| MBD: tetragonal (0,155R) | 0,9323 | 0,4501 | 14,66 | 0,2326 | 0,0010 |
| MBD: cubical (0,732R) | 0,3072 | 1,8167 | 2,43 | 0,2013 | 0,1942 |
| MBD: cubical tetrahedral (0,531R) | 0,4787 | 1,4675 | 5,10 | 0,2134 | 0,0582 |
| MBD: tetragonal (0,285R) | 1,0048 | 0,4028 | 17,96 | 0,2221 | 0,0002 |
| MBD: pyramidal/ tetrahedral (0,414R) | 0,0911 | 2,1108 | 0,20 | 0,2094 | 0,7097 |
| Random BD (not corrected for org. mat.) | 0,3914 | 1,0058 | 38,25 | 0,0514 | 0,0000 |
| Random BD (corrected for org. mat.) | 0,4282 | 0,8489 | 26,01 | 0,0747 | 0,0000 |
| Minimum BD (not corrected for org. mat.) | 0,1420 | 1,1237 | 6,43 | 0,0560 | 0,0328 |
| Minimum BD (corrected for org. mat.) | 0,1783 | 1,0010 | 6,65 | 0,0691 | 0,0299 |

a) Input data: <6 mm textural fractions + gravel (Appendix 3); measured particle and bulk densities for different fractions (Appendices 6 and 7); fine silt BD = 1,300 $Mg\ m^{-3}$; clay BD = 1,200 $Mg\ m^{-3}$.

b) For different packing arrangements compare Fig. 1.2.

Table 6.2. Statistical evaluation of the random packing model when using different input data to predict field bulk density of 68 soils sampled for a compaction study.[a]

| Number of and variation in packing model[b] | Slope | Inter- cept | Correlation coefficient (r) | Standard error of estimate | Root mean square error | Index of agreememt (d) | Average | Standard deviation | Range |
|---|---|---|---|---|---|---|---|---|---|
| 1) Measured PD & BD; <2 mm; - GR | 0,208 | 1,290 | 0,424 | 0,067 | 0,137 | 0,583 | 1,636 | 0,073 | 0,408 |
| 2) Measured PD & BD; <2 mm; + GR | 0,270 | 1,203 | 0,485 | 0,074 | 0,131 | 0,642 | 1,652 | 0,083 | 0,447 |
| 3) Measured PD & BD; <6 mm; - GR | 0,213 | 1,283 | 0,413 | 0,071 | 0,138 | 0,580 | 1,638 | 0,077 | 0,426 |
| 4) Measured PD & BD; <6 mm; + GR | 0,276 | 1,195 | 0,474 | 0,078 | 0,132 | 0,644 | 1,655 | 0,086 | 0,418 |
| 5) Average PD & BD; <2 mm; + GR | 0,258 | 1,215 | 0,437 | 0,080 | 0,137 | 0,622 | 1,645 | 0,087 | 0,447 |
| 6) Average PD & BD; <6 mm; + GR | 0,245 | 1,242 | 0,419 | 0,080 | 0,138 | 0,608 | 1,649 | 0,086 | 0,454 |
| 7) Measured BD; Average PD; <6 mm; + GR | 0,283 | 1,182 | 0,480 | 0,078 | 0,132 | 0,657 | 1,653 | 0,087 | 0,464 |
| 8) Average BD; Measured PD; <6 mm; + GR | 0,230 | 1,262 | 0,413 | 0,077 | 0,138 | 0,592 | 1,644 | 0,082 | 0,430 |
| 9) Measured BD; PD's = 2,65; <6 mm; + GR | 0,275 | 1,194 | 0,460 | 0,080 | 0,134 | 0,641 | 1,651 | 0,088 | 0,429 |
| 10) Do. 4, but clay BD = 1,00 | 0,295 | 1,123 | 0,500 | 0,077 | 0,138 | 0,647 | 1,613 | 0,087 | 0,437 |
| 11) Do. 4, but clay BD = 1,10 | 0,285 | 1,161 | 0,493 | 0,076 | 0,132 | 0,647 | 1,635 | 0,086 | 0,425 |
| 12) Do. 4, but clay BD = 1,30 | 0,269 | 1,224 | 0,450 | 0,081 | 0,135 | 0,640 | 1,672 | 0,088 | 0,438 |
| 13) Do. 4, but clay BD = 1,40 | 0,262 | 1,251 | 0,423 | 0,085 | 0,141 | 0,629 | 1,686 | 0,092 | 0,459 |
| 14) Do. 4, but clay BD = 1,50 | 0,255 | 1,274 | 0,396 | 0,089 | 0,147 | 0,614 | 1,700 | 0,095 | 0,478 |
| 15) Do. 4, but fine silt BD = 1,10 | 0,277 | 1,173 | 0,460 | 0,081 | 0,136 | 0,639 | 1,633 | 0,089 | 0,456 |
| 16) Do. 4, but fine silt BD = 1,20 | 0,285 | 1,169 | 0,479 | 0,079 | 0,133 | 0,653 | 1,643 | 0,088 | 0,471 |
| 17) Do. 4, but fine silt BD = 1,40 | 0,243 | 1,253 | 0,439 | 0,075 | 0,135 | 0,616 | 1,658 | 0,082 | 0,408 |
| 18) Do. 4, but fine silt BD = 1,50 | 0,264 | 1,228 | 0,475 | 0,074 | 0,132 | 0,633 | 1,668 | 0,082 | 0,400 |
| Maximum Proctor BD | - | - | 0,538 | 0,082 | 0,259 | 0,490 | 1,882 | 0,103 | 0,480 |
| Field BD | - | - | - | - | - | - | 1,657 | 0,150 | 0,773 |

[a] The terms r and d are dimensionless while the remaining measures have the units Mg $m^{-3}$.

[b] 1) Measured and average particle densities (PD) of different fractions as per Appendix 6, and measured and average maximum bulk densities (BD) of different fractions as per Appendix 7.

2) Unless otherwise stated, fine silt BD = 1,300 Mg $m^{-3}$ and clay BD = 1,200 Mg $m^{-3}$.

3) <2 mm and <6 mm textural fractions as per Appendices 2 and 3, respectively.

4) + GR or - GR = with or without gravel (2-6 mm).

Table 6.3. Variation in the predicted maximum (cavity size of 0,285R[a]), and random bulk densities (BD) due to varying fine silt BD's for selected soils arranged in descending order with regard to fine silt content. (Except for the varying BD's of the fine silt fraction, the input to the model were the same as for the one in Table 6.1)[b].

| Soil no. | % fine silt[c] (0,020-0,002 mm) | Pred. max. BD at different fine silt BD's (Mg $m^{-3}$) 1,10 | 1,20 | 1,30 | 1,40 | 1,50 | Max. BD (Mg $m^{-3}$) | Pred. random BD at different fine silt BD's (Mg $m^{-3}$) 1,10 | 1,20 | 1,30 | 1,40 | 1,50 | Field BD (Mg $m^{-3}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 16 | 29,31 | 2,286 | 2,379 | 2,465 | 2,543 | 2,615 | 1,992 | 1,605 | 1,658 | 1,703 | 1,690 | 1,764 | 1,868 |
| 3 | 28,38 | 2,381 | 2,457 | 2,525 | 2,587 | 2,644 | 1,767 | 1,488 | 1,523 | 1,545 | 1,586 | 1,608 | 1,642 |
| 15 | 27,34 | 2,253 | 2,342 | 2,422 | 2,495 | 2,562 | 1,917 | 1,577 | 1,612 | 1,647 | 1,695 | 1,729 | 1,675 |
| 41 | 19,99 | 2,379 | 2,460 | 2,532 | 2,598 | 2,658 | 1,838 | 1,505 | 1,510 | 1,533 | 1,527 | 1,593 | 1,555 |
| 4 | 17,94 | 2,585 | 2,585 | 2,585 | 2,585 | 2,585 | 1,975 | 1,672 | 1,696 | 1,708 | 1,726 | 1,740 | 1,947 |
| 52 | 15,69 | 2,219 | 2,219 | 2,219 | 2,219 | 2,219 | 1,785 | 1,523 | 1,548 | 1,574 | 1,567 | 1,570 | 1,444 |
| 48 | 14,32 | 2,013 | 2,013 | 2,013 | 2,013 | 2,013 | 1,600 | 1,669 | 1,705 | 1,690 | 1,687 | 1,706 | - |
| 8 | 12,77 | 2,233 | 2,192 | 2,159 | 2,132 | 2,109 | 1,808 | 1,652 | 1,642 | 1,655 | 1,668 | 1,675 | 1,764 |
| 51 | 12,28 | 2,472 | 2,472 | 2,472 | 2,472 | 2,472 | 1,785 | 1,495 | 1,551 | 1,537 | 1,541 | 1,539 | 1,328 |
| 59 | 11,45 | 2,362 | 2,362 | 2,362 | 2,362 | 2,362 | 1,881 | 1,517 | 1,557 | 1,560 | 1,583 | 1,562 | 1,724 |
| 21 | 10,29 | 2,046 | 2,046 | 2,046 | 2,046 | 2,046 | 1,881 | 1,582 | 1,569 | 1,533 | 1,590 | 1,598 | 1,710 |
| 33 | 8,99 | 1,973 | 1,973 | 1,973 | 1,973 | 1,973 | 1,825 | 1,719 | 1,756 | 1,731 | 1,750 | 1,757 | 1,805 |
| 36 | 7,27 | 2,211 | 2,211 | 2,211 | 2,211 | 2,211 | 1,873 | 1,516 | 1,577 | 1,539 | 1,577 | 1,554 | 1,619 |
| 25 | 5,80 | 1,962 | 1,962 | 1,962 | 1,962 | 1,962 | 1,840 | 1,699 | 1,709 | 1,669 | 1,722 | 1,707 | 1,572 |
| 1 | 5,80 | 1,822 | 1,822 | 1,822 | 1,822 | 1,822 | 1,676 | 1,594 | 1,600 | 1,605 | 1,592 | 1,595 | 1,607 |
| 26 | 3,68 | 2,613 | 2,613 | 2,613 | 2,613 | 2,613 | 2,006 | 1,763 | 1,759 | 1,743 | 1,742 | 1,775 | 1,653 |
| 54 | 2,34 | 2,439 | 2,439 | 2,439 | 2,439 | 2,439 | 1,940 | 1,636 | 1,607 | 1,648 | 1,650 | 1,677 | 1,625 |
| 68 | 2,19 | 2,014 | 2,014 | 2,014 | 2,014 | 2,014 | 1,915 | 1,543 | 1,547 | 1,554 | 1,543 | 1,564 | 1,828 |
| 20 | 1,21 | 2,473 | 2,473 | 2,473 | 2,473 | 2,473 | 1,839 | 1,758 | 1,778 | 1,785 | 1,780 | 1,801 | 1,716 |
| 69 | 1,08 | 1,945 | 1,945 | 1,945 | 1,945 | 1,945 | 1,925 | 1,569 | 1,568 | 1,556 | 1,571 | 1,559 | 1,722 |

a) 0,285R = Radius of cavity for tetragonal packing, with 0,285 = Void size factor and R = Average radius of particle (Gupta and Larson, 1979).

b) Input data = <6 mm textural data + gravel (Appendix 3); measured particle and bulk densities for different fractions (Appendices 6 and 7); clay BD = 1,200 Mg $m^{-3}$; varying BD's for fine silt fraction.

c) <6 mm basis.

Table 6.4. Variation in the predicted maximum (cavity size of 0,285R[a]), and random bulk densities (BD) due to varying clay BD's for selected soils arranged in descending order with regard to clay content. (Except for the varying BD's of the clay fraction, the input to the model were the same as for the one in Table 6.1)[b].

| Soil No. | % Clay[c] (<0,002 mm) | Pred. max. BD at different clay BD's (Mg m$^{-3}$) 1,00 | 1,10 | 1,20 | 1,30 | 1,40 | 1,50 | Max. BD (Mg m$^{-3}$) | Pred. random BD at different clay BD's (Mg m$^{-3}$) 1,00 | 1,10 | 1,20 | 1,30 | 1,40 | 1,50 | Field BD (Mg m$^{-3}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 22 | 34,67 | 1,996 | 1,996 | 1,996 | 1,996 | 1,996 | 1,996 | 1,719 | 1,525 | 1,538 | 1,550 | 1,559 | 1,568 | 1,576 | 1,459 |
| 25 | 33,67 | 1,790 | 1,880 | 1,962 | 2,038 | 2,107 | 2,171 | 1,840 | 1,570 | 1,623 | 1,669 | 1,711 | 1,748 | 1,782 | 1,572 |
| 8 | 30,14 | 2,018 | 2,093 | 2,159 | 2,219 | 2,273 | 2,322 | 1,808 | 1,576 | 1,618 | 1,655 | 1,688 | 1,717 | 1,744 | 1,764 |
| 33 | 29,24 | 1,804 | 1,893 | 1,973 | 2,047 | 2,115 | 2,178 | 1,825 | 1,649 | 1,693 | 1,731 | 1,765 | 1,795 | 1,822 | 1,805 |
| 52 | 27,84 | 2,084 | 2,156 | 2,219 | 2,275 | 2,326 | 2,371 | 1,785 | 1,509 | 1,544 | 1,574 | 1,600 | 1,624 | 1,645 | 1,444 |
| 48 | 27,74 | 1,848 | 1,935 | 2,013 | 2,085 | 2,151 | 2,212 | 1,600 | 1,613 | 1,654 | 1,690 | 1,722 | 1,750 | 1,775 | - |
| 13 | 26,19 | 2,110 | 2,175 | 2,233 | 2,284 | 2,329 | 2,370 | 1,895 | 1,706 | 1,748 | 1,785 | 1,818 | 1,847 | 1,873 | 2,042 |
| 21 | 25,85 | 1,886 | 1,970 | 2,046 | 2,115 | 2,178 | 2,236 | 1,881 | 1,468 | 1,503 | 1,533 | 1,559 | 1,583 | 1,604 | 1,710 |
| 7 | 21,44 | 2,163 | 2,224 | 2,277 | 2,324 | 2,366 | 2,404 | 1,947 | 1,612 | 1,641 | 1,666 | 1,687 | 1,706 | 1,723 | 1,743 |
| 15 | 20,22 | 2,422 | 2,422 | 2,422 | 2,422 | 2,422 | 2,422 | 1,917 | 1,596 | 1,623 | 1,647 | 1,668 | 1,686 | 1,702 | 1,675 |
| 26 | 19,23 | 2,613 | 2,613 | 2,613 | 2,613 | 2,613 | 2,613 | 2,006 | 1,689 | 1,718 | 1,743 | 1,764 | 1,783 | 1,799 | 1,653 |
| 54 | 15,92 | 2,366 | 2,405 | 2,439 | 2,468 | 2,494 | 2,517 | 1,940 | 1,606 | 1,628 | 1,648 | 1,664 | 1,678 | 1,691 | 1,625 |
| 59 | 15,85 | 2,267 | 2,318 | 2,362 | 2,401 | 2,435 | 2,465 | 1,881 | 1,524 | 1,544 | 1,560 | 1,574 | 1,586 | 1,597 | 1,724 |
| 41 | 14,57 | 2,532 | 2,532 | 2,532 | 2,532 | 2,535 | 2,532 | 1,838 | 1,501 | 1,532 | 1,533 | 1,546 | 1,557 | 1,567 | 1,555 |
| 51[d] | 13,42 | 2,472 | 2,472 | 2,472 | 2,472 | 2,472 | 2,472 | 1,785 | 1,508 | 1,524 | 1,537 | 1,549 | 1,559 | 1,568 | 1,328 |
| 17 | 13,09 | 2,558 | 2,558 | 2,558 | 2,558 | 2,558 | 2,558 | 1,944 | 1,626 | 1,645 | 1,661 | 1,674 | 1,687 | 1,697 | 1,615 |
| 35 | 10,01 | 2,472 | 2,496 | 2,517 | 2,534 | 2,549 | 2,563 | 2,023 | 1,719 | 1,732 | 1,744 | 1,754 | 1,762 | 1,770 | 1,670 |
| 6[d] | 7,08 | 2,146 | 2,146 | 2,146 | 2,146 | 2,146 | 2,146 | 2,034 | 1,565 | 1,574 | 1,581 | 1,588 | 1,593 | 1,598 | 1,541 |
| 68 | 5,17 | 2,014 | 2,014 | 2,014 | 2,014 | 2,014 | 2,014 | 1,915 | 1,543 | 1,549 | 1,554 | 1,558 | 1,562 | 1,565 | 1,828 |
| 1 | 4,44 | 1,822 | 1,822 | 1,822 | 1,822 | 1,822 | 1,822 | 1,676 | 1,597 | 1,601 | 1,605 | 1,608 | 1,611 | 1,613 | 1,607 |
| 69 | 4,44 | 1,945 | 1,945 | 1,945 | 1,945 | 1,945 | 1,945 | 1,925 | 1,547 | 1,552 | 1,556 | 1,560 | 1,563 | 1,566 | 1,722 |
| 10 | 2,29 | 2,639 | 2,639 | 2,639 | 2,639 | 2,639 | 2,639 | 1,878 | 1,639 | 1,696 | 1,699 | 1,702 | 1,705 | 1,707 | 1,680 |
| 20 | 1,13 | 2,473 | 2,473 | 2,473 | 2,473 | 2,473 | 2,473 | 1,839 | 1,783 | 1,784 | 1,785 | 1,787 | 1,788 | 1,788 | 1,716 |

[a] 0,285R = Radius of cavity for tetragonal packing, with 0,285 = Void size factor and R = Average radius of particle (Gupta and Larson, 1979).

[b] Input data = <6 mm textural data + gravel (Appendix 3); measured particle and bulk densities for different fractions (Appendices 6 and 7); clay BD = 1,200 Mg m$^{-3}$; varying BD's for fine silt fraction.

[c] <6 mm basis.

[d] Soil was loose at the time of sampling.

Table 6.5. List of soils whose field bulk densities were outside the 1 x S.E.E. limit (±0,08 Mg $m^{-3}$) of the 1:1 line relating FBD's to the random bulk densities predicted from the packing model of Gupta and Larson (1979).

| | Bulk density (Mg $m^{-3}$) | | | | |
|---|---|---|---|---|---|
| Soil no.[a] | Max. predicted | Max. Proctor | Random predicted | Field measured | Most prominent soil properties/conditions relating soils within a group |
| 14 | 2,352 | 1,975 | 1,655 | 1,947 | Loosened shortly prior to sampling. |
| 38 | 2,001 | 1,825 | 1,668 | 1,269 | |
| 44 | 2,082 | 1,816 | 1,696 | 1,370 | |
| 49 | 2,619 | 1,800 | 1,571 | 1,387 | |
| 51 | 2,472 | 1,785 | 1,537 | 1,328 | |
| 22 | 1,894 | 1,795 | 1,668 | 1,554 | Undisturbed, well-drained, naturally compact, red and yellow subsoils. |
| 23 | 1,928 | 1,828 | 1,723 | 1,513 | |
| 25 | 1,962 | 1,840 | 1,669 | 1,572 | |
| 26 | 2,613 | 2,006 | 1,743 | 1,653 | |
| 27 | 2,086 | 1,956 | 1,753 | 1,685 | |
| 39 | 2,058 | 1,830 | 1,666 | 1,597 | |
| 4 | 2,336 | 1,975 | 1,766 | 1,947 | 60,4% Total sand;[b] Kurtosis = 3,53.[c] |
| 47 | 2,479 | 2,050 | 1,678 | 1,860 | 80,1% Total sand; Kurtosis = 4,18. |
| 59 | 2,362 | 1,881 | 1,560 | 1,724 | 59,0% Total sand; Kurtosis = 2,55. |
| 61 | 2,232 | 1,836 | 1,583 | 1,741 | 74,9% Total sand; Kurtosis = 4,12. |
| 62 | 2,173 | 1,958 | 1,568 | 1,783 | 86,4% Total sand; Kurtosis = 5,82. |
| 63 | 2,510 | 2,005 | 1,761 | 1,855 | 87,7% Total sand; Kurtosis = 5,72. |
| 68 | 2,014 | 1,915 | 1,554 | 1,828 | 91,3% Total sand; Kurtosis = 8,86. |
| 69 | 1,945 | 1,925 | 1,556 | 1,722 | 92,9% Total sand; Kurtosis = 10,49. |
| 3 | 2,525 | 1,767 | 1,545 | 1,642 | MOR1[d] = 88,9; MOR2[e] = 398,5; AWR[f] = 150. |
| 21 | 2,046 | 1,881 | 1,533 | 1,710 | MOR1 = 16,3; MOR2 = 268,1; AWR = 79. |
| 31 | 2,576 | 2,006 | 1,731 | 1,845 | MOR1 = 12,7; MOR2 = 242,7; AWR = 48. |
| 67 | 2,100 | 1,838 | 1,534 | 1,925 | MOR1 = 6,1; MOR2 = 304,5; AWR = 49. |
| 8 | 2,159 | 1,808 | 1,655 | 1,764 | 38,8% Clay; Young weathering C horizon. |
| 13 | 2,233 | 1,895 | 1,785 | 2,042 | 28,1% Clay; Hydromorphic gleyed horizon. |
| 16 | 2,465 | 1,992 | 1,703 | 1,868 | 18,5% Clay; Hydromorphic gleyed horizon. |

[a] Soil numbers, origin and morphological poperties listed in Appendix 1 and Table 4.1.
[b] Total sand on <2 mm basis (Appendix 2).
[c] Moment coefficient of kurtosis on <6 mm basis (Appendix 9).
[d] Modulus of rupture after one hour soaking time. (Table 4.3).
[e] Modulus of rupture after 12 hours soaking time. (Table 4.3).
[f] Air-to-water permeability ratio (Table 5.1).

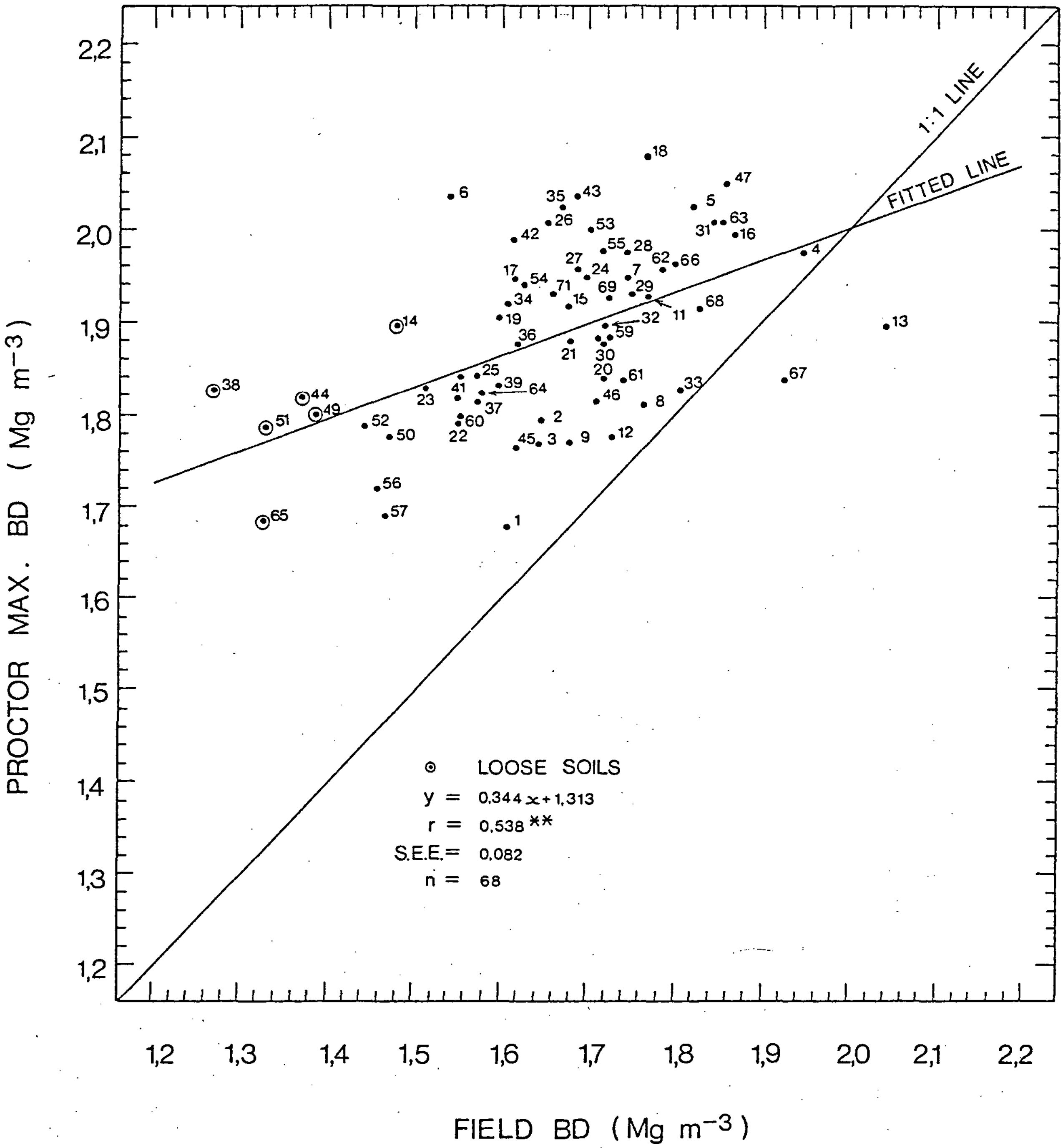


Fig. 6.1. Relationship between Proctor maximum bulk density (MBD) and field bulk density (FBD) for 68 soils used in a compaction study.

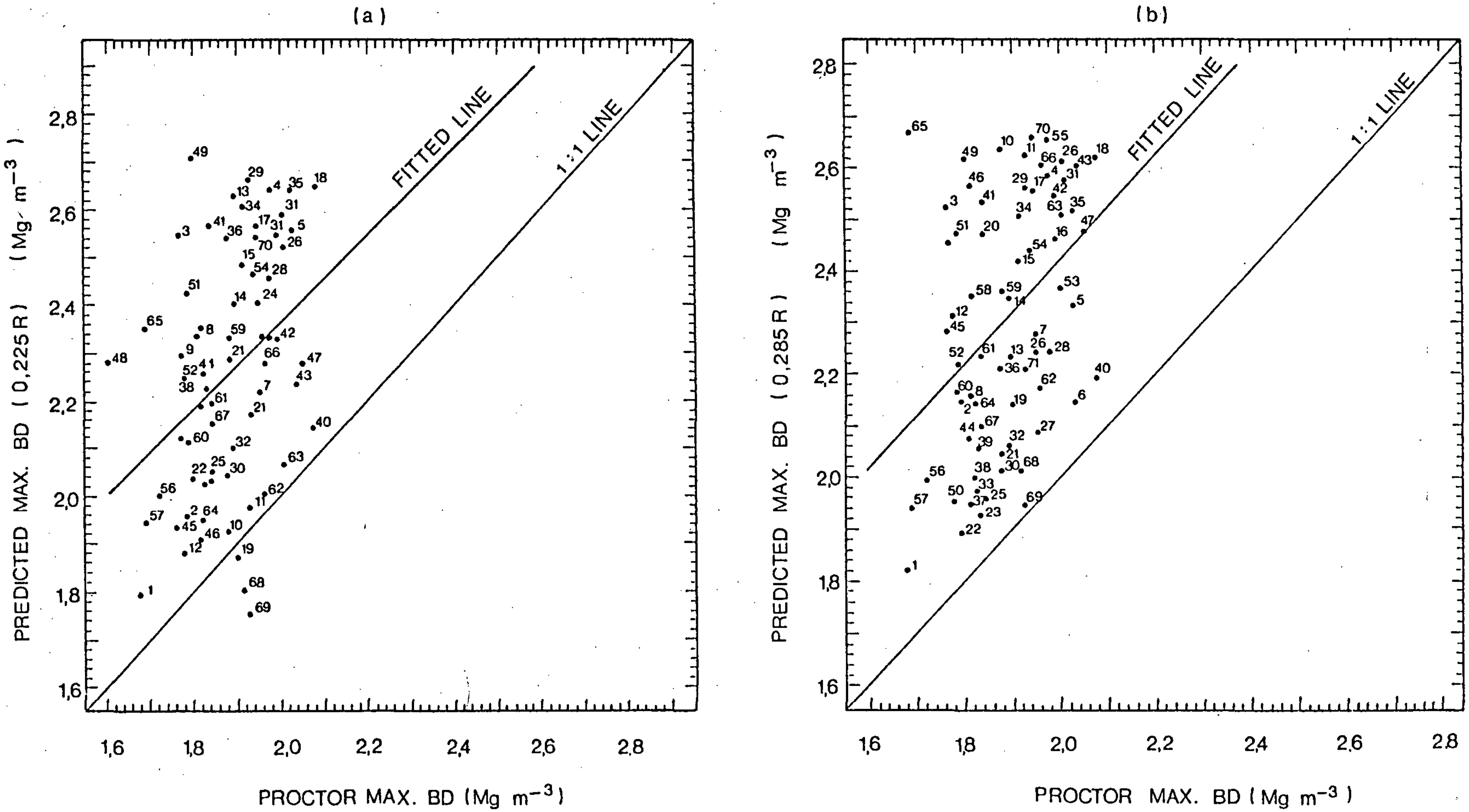


Fig. 6.2. Relationship between predicted maximum bulk density and Proctor maximum bulk density for 71 soils used in a compaction study: (a) Pyramidal/tetrahedral packing arrangement. (b) Tetragonal packing arrangement.

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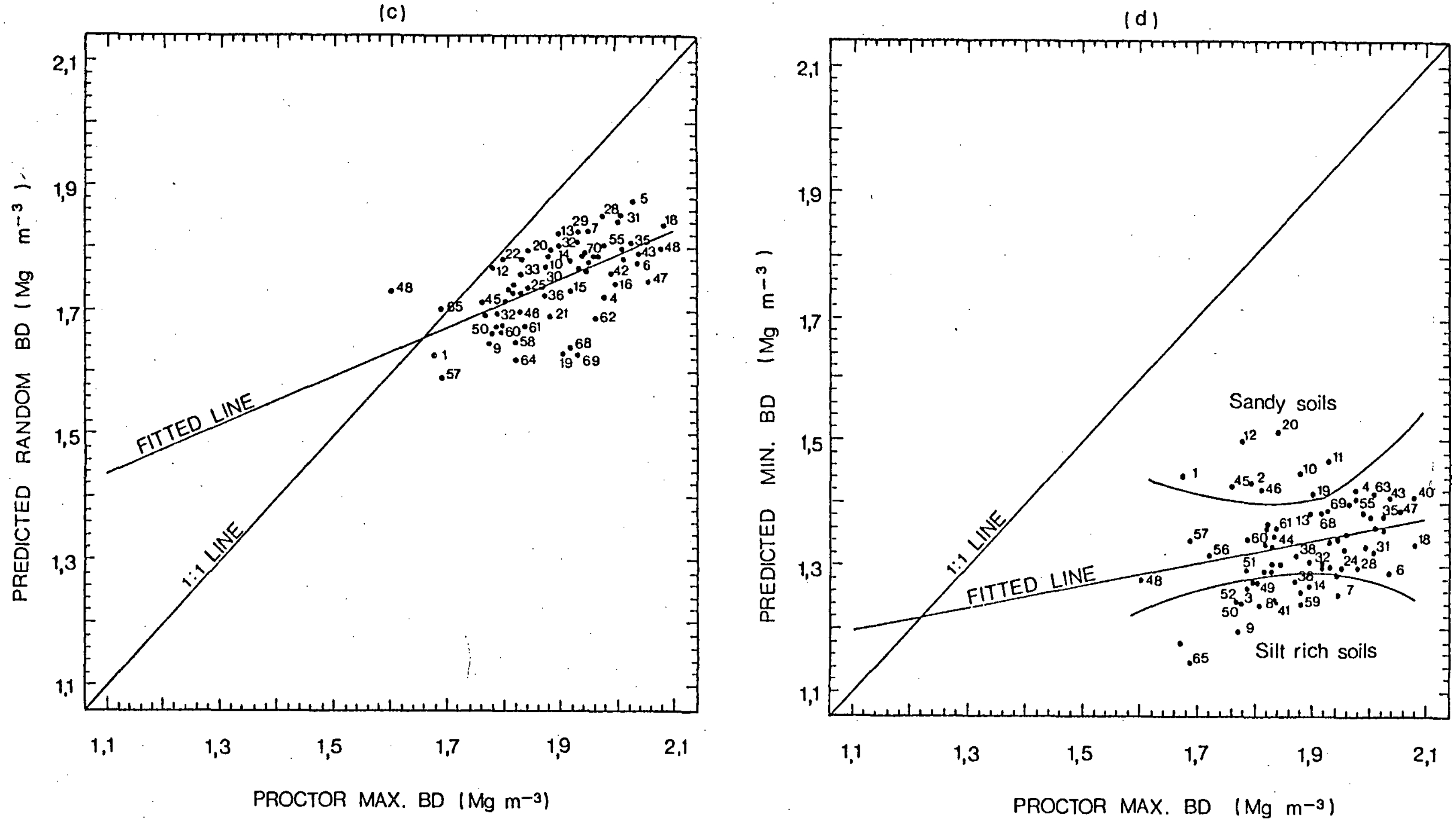


Fig. 6.2. Continued. Relationship between predicted bulk density and Proctor maximum bulk density for 71 soils used in a compaction study: (c) Random packing arrangement of individual particles. (d) Loosest possible packing of particles.

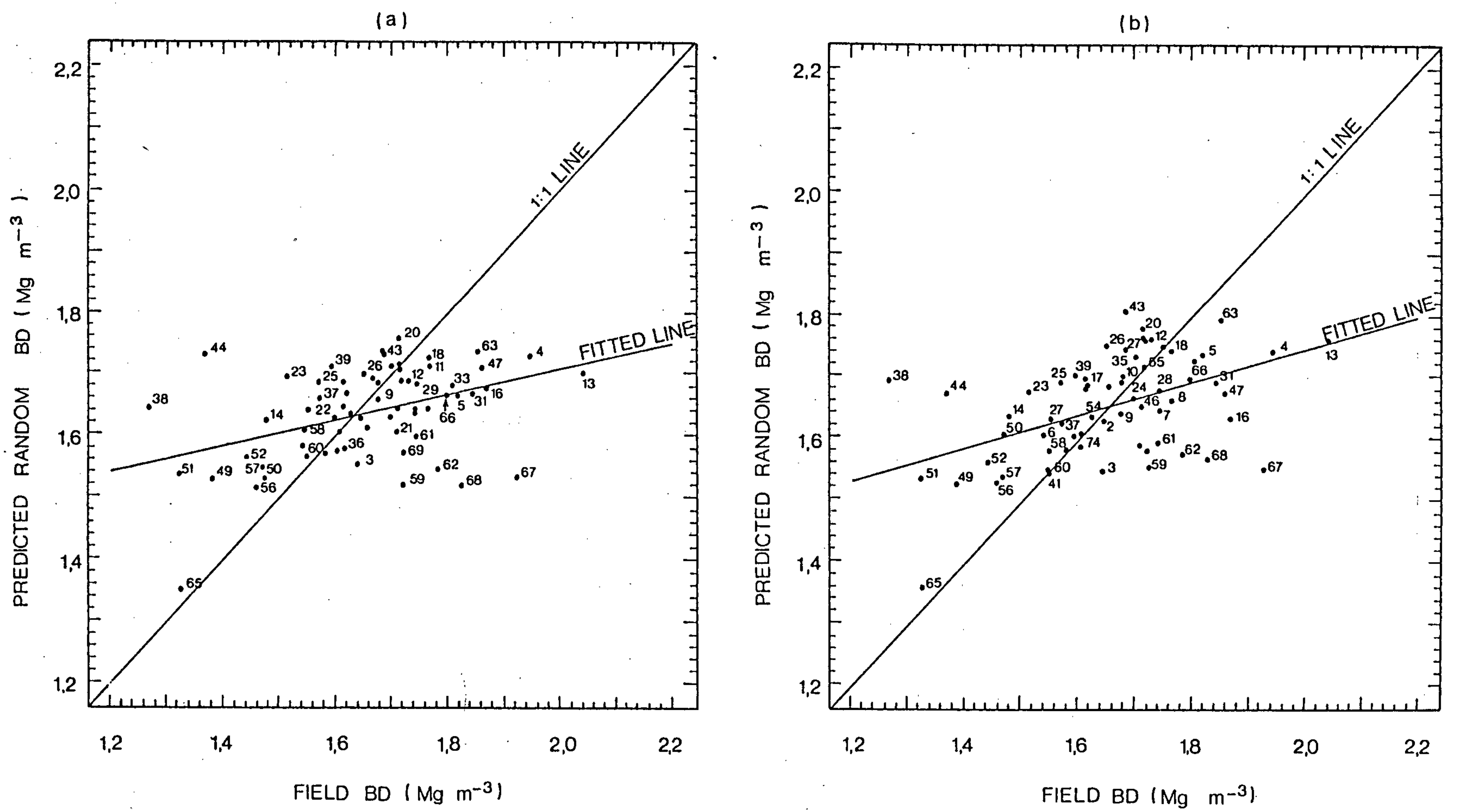


Fig. 6.3. Relationship between predicted random bulk density and field bulk density for different input data variations: (a) Input data as for model no. 1 in Table 6.2. (b) Input data as for model no. 2 in Table 6.2.

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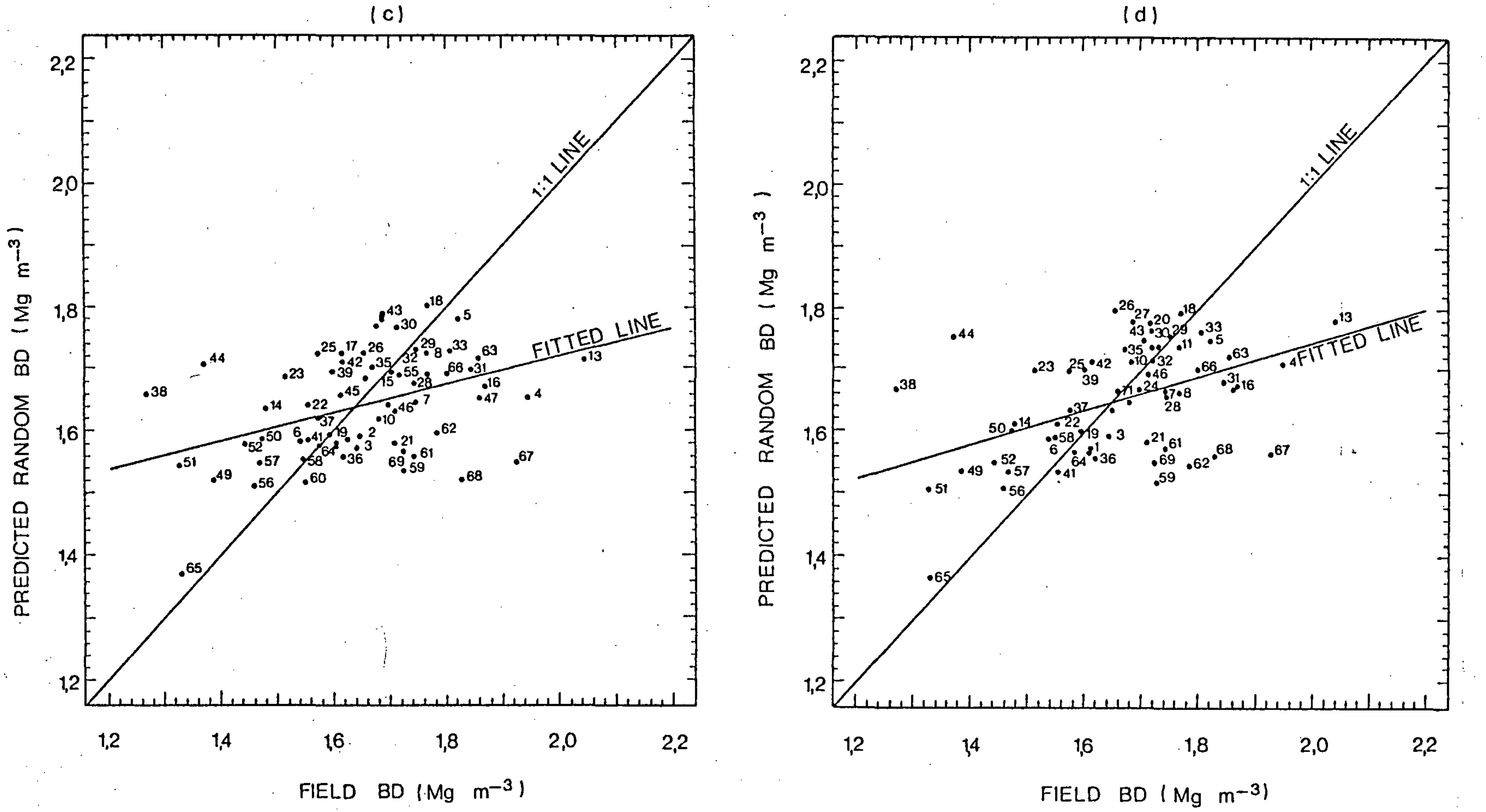


Fig. 6.3. Continued. Relationship between predicted random bulk density and field bulk density for different input data variations: (c) Input as for model no. 8 in Table 6.2. (d) Input as for model no. 9 in Table 6.2.

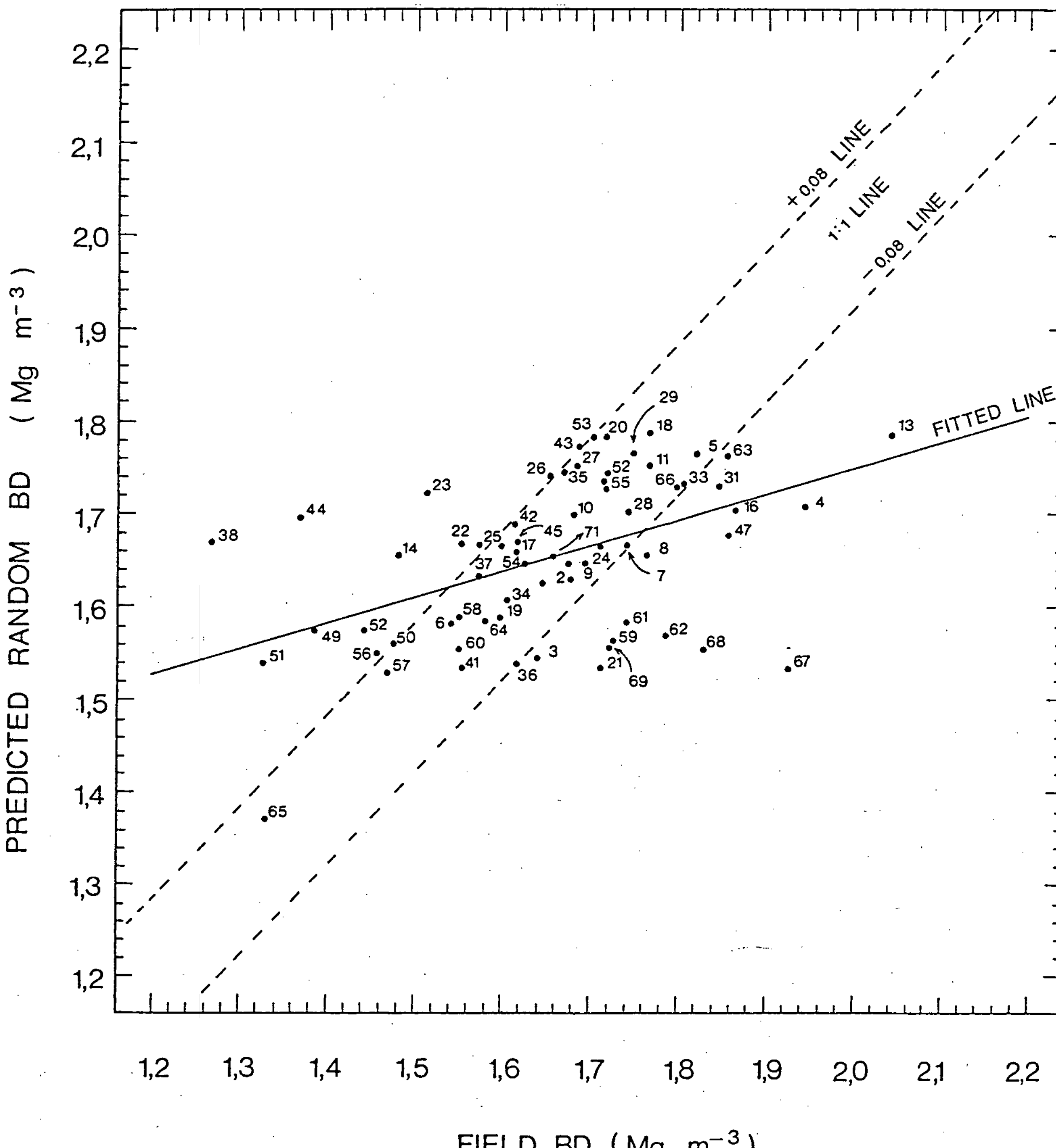


Fig. 6.4. Relationship between predicted random bulk density and measured field bulk density for 68 soils used in a compaction study.

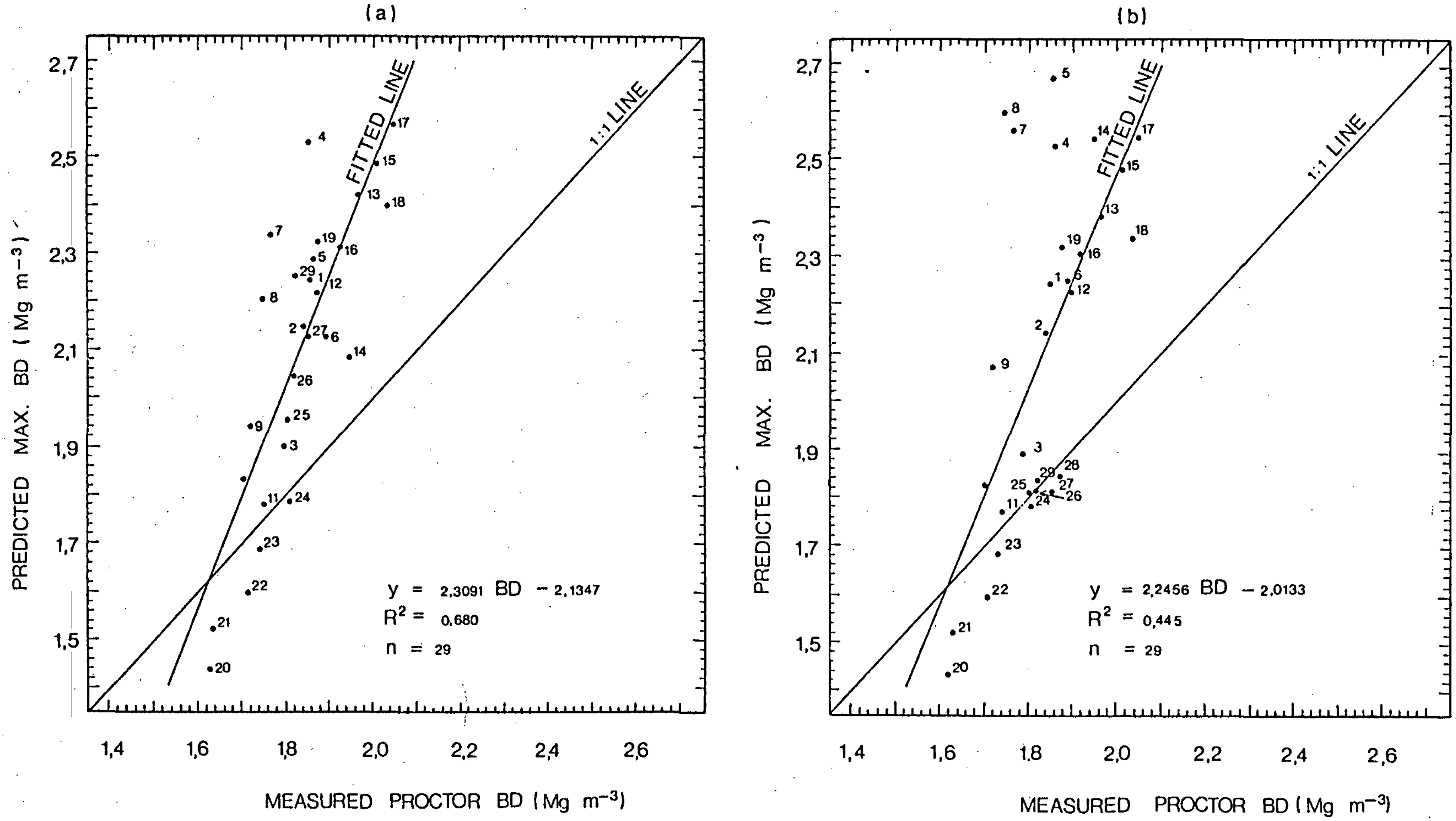


Fig. 6.5. Comparison of predicted maximum bulk density from different packing arrangements of particles with Proctor maximum bulk density (MBD) of 29 soils from Moolman (1981): (a) Pyramidal with cavity size 0,225R. (b) Tetragonal with cavity size 0,155R.

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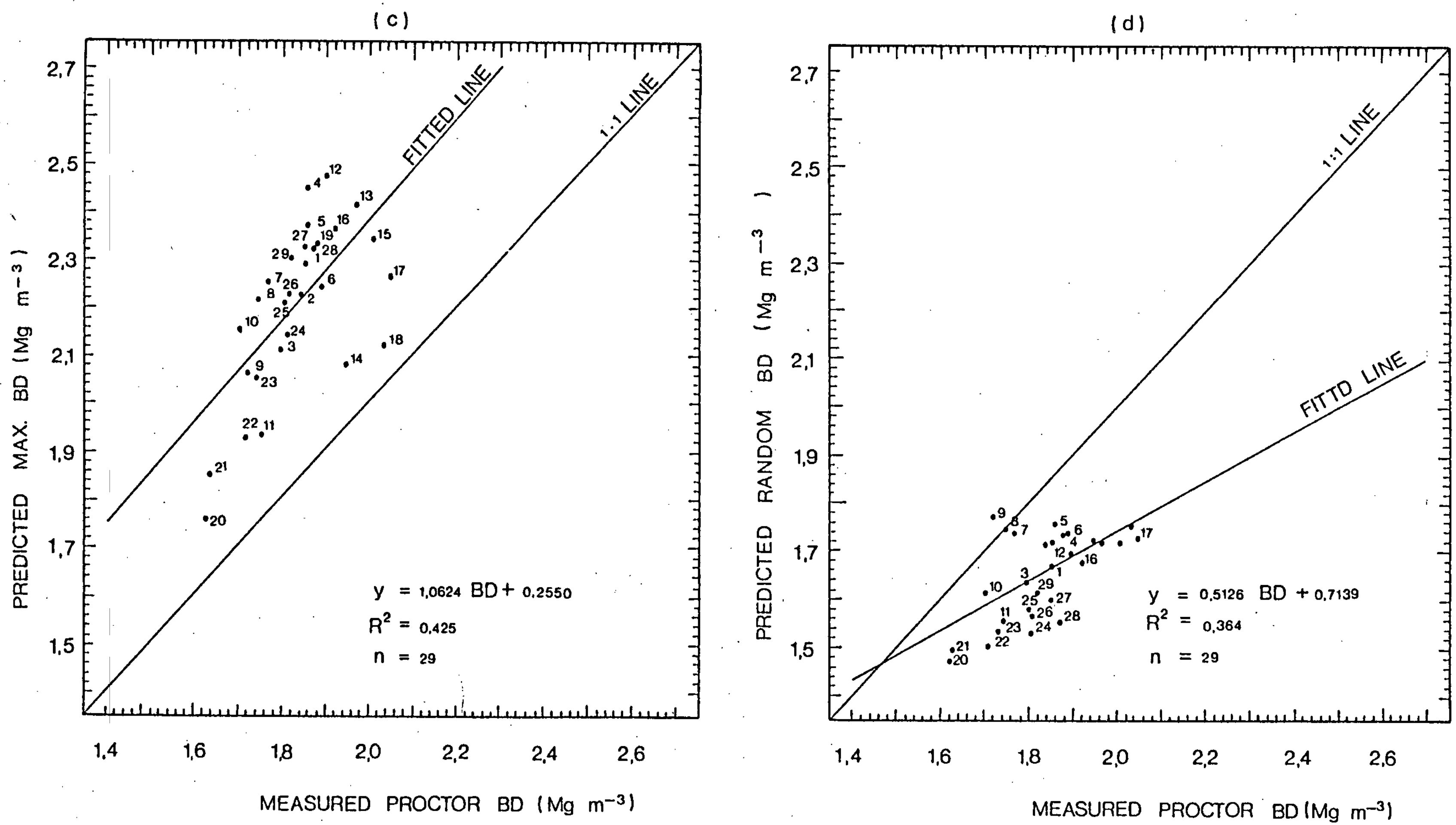


Fig. 6.5. Continued. Comparison of predicted maximum bulk density from different packing arrangements of particles with Proctor maximum bulk density (MBD) of 29 soils from Moolman (1981): (c) Tetrahedral with cavity size 0,414R. (d) Random arrangement.

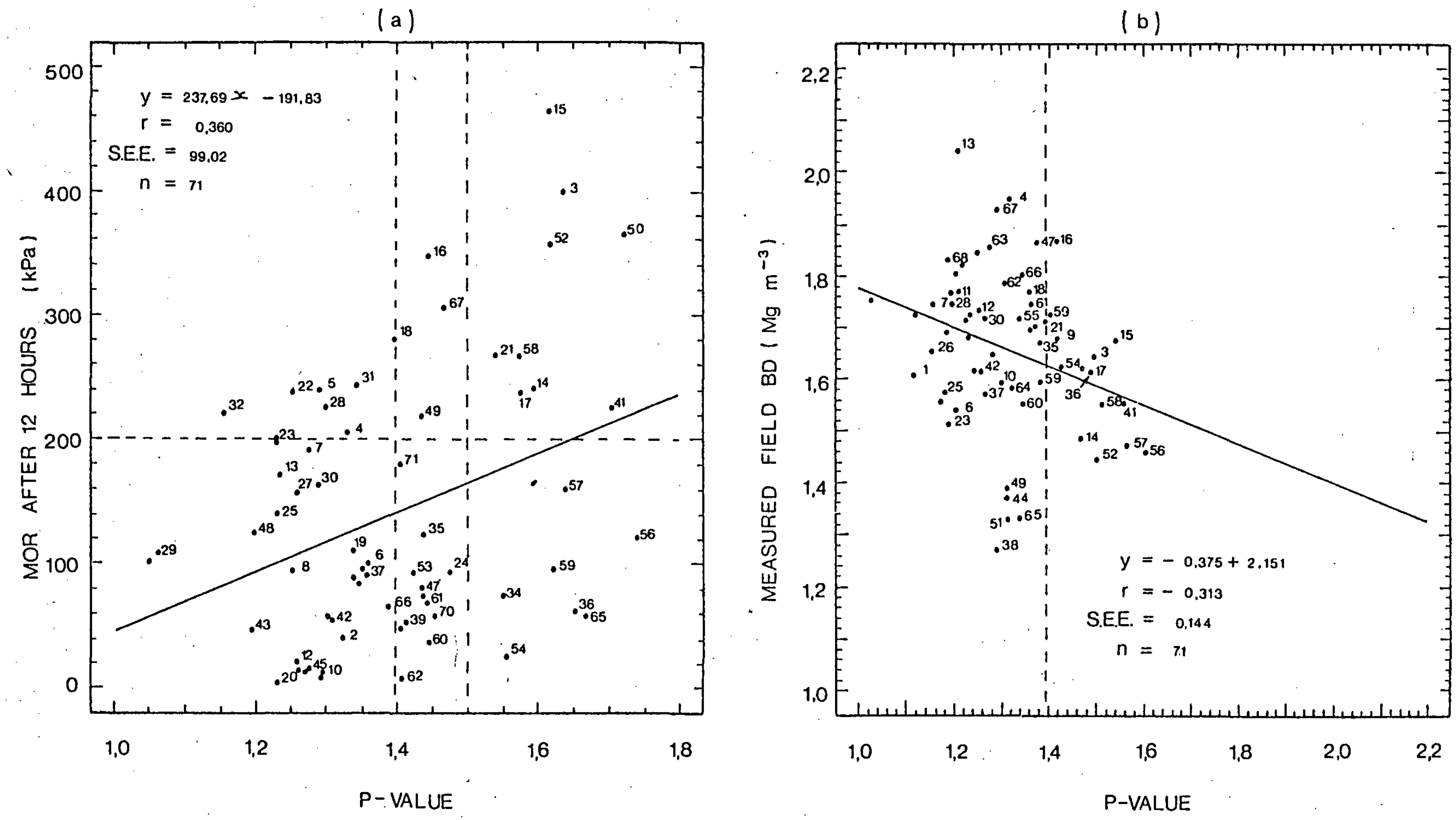


Fig. 6.6. Relationships between a) modulus of rupture after 12 hours soaking time and P-value, and between b) field bulk density and P-value for soils used in a compaction study.

# CHAPTER 7

# GENERAL CONCLUSIONS AND RECOMMENDATIONS

Each chapter has been provided with its own specific summary and conclusions. This chapter, therefore, is aimed at (i) providing a general overview of the study, (ii) to list the general conclusions that have been drawn, and (iii) to make suggestions for future research.

## 7.1 SCOPE OF THIS STUDY

Soil compaction is a problem common to many vineyard soils, and it has substantial adverse effects on root growth. For this reason, in practical viticulture deep ploughing is used to break up compacted horizons. However, deep ploughing do have limitations - in particular the high costs thereof. Equally limiting is the short duration of the loosening effect on some soils. It is very difficult and expensive to rectify poor soil physical conditions once the vineyard, a long-term crop, has been established. Therefore, the problem of recompaction is of particular concern to the viticulturist. With the implements presently available, about every degree of loosening and all types of mixing can be obtained in the soil profile, but the decision-making can be fully justified only if the nature of the soils' compactibility is understood. Therefore, the sensitivity of vineyard soils to compaction needs to be assessed before the vineyard is being established.

The emphasis of research on soil management in vineyards in the past has been heavily on the description of the effects of various tillage practices on vine performance, with relatively little attempt to understand and analyse the mechanisms involved in changes of the soil condition. The purpose of this research was to provide a broad introduction of soil compaction in viticulture by investigating selected physical/mechanical properties of the soil. It was hypothesised that natural soil properties, such as texture, determine the compactibility of vineyard soils, which in turn regulates compaction and root impedance, both factors of crucial importance if decisions on soil management techniques are to be made and evaluated in a cost-conscious way. This study distinguishes itself from other similar studies in that a wide variety of soils are studied instead of concentrating on a particular soil group. However, several important aspects of soil mechanics, *e.g.* soil compressibility, have deliberately been avoided in order to keep for this project manageable.

## 7.2 GENERAL CONCLUSIONS

Some of the most prominent conclusions from this investigation are summarised as follows:

1) The soils studied in this investigation differed in their susceptibility to compaction because of textural differences.

2) Root growth decreased linearly with increasing compaction. The number of grapevine roots was primarily determined by the size and quality of the rooting medium, which, in turn, was influenced by soil compaction.

3) Cause and severity of soil compaction may vary with soil type. Even subtle changes in soil properties, *e.g.* increase in fine sand, may cause marked changes in soil bulk densities and rooting patterns.

4) Soil properties that are useful in describing compactibility and the recognition of structural instability are particle size analysis data, air-to-water permeability ratio and modulus of rupture. However, compaction was not necessarily associated with structural instability.

5) Mechanical analysis data readily translated into standard and useful statistical information that characterises particle size distribution. It was possible to use a multiple regression equation, based on textural data, to predict Proctor maximum bulk density. The 2 to 6 mm particle size class should be included for compactibility studies.

6) The Gupta-Larson packing model was successful in predicting field bulk density, within one standard error of estimate (0,08 Mg $m^{-3}$), for the majority of soils studied. The model is simple to use and can be easily applied in practice. The model makes it possible to establish a better understanding of the relationship between soil texture and equilibrium soil bulk density.

7) An important outcome of this study was the identification of definite soil groups differing in their sensitivity to compaction and thus compactibility. The different soil groups identified were: silt rich alluvial soils from the hot and dry interior irrigation areas, sandy soils with more than 60% total sand (<2 mm basis); topsoils with hardsetting characteristics; and subsoils into which clay illuviation has taken place.

8) Model evaluation was done within the linear frame, since none of the scatterplots suggests that any of the relationships between observed and predicted values is nonlinear.

9) Despite shortcomings, it has been proved that the joint prediction of maximum potential bulk density by regression and the prediction of equilibrium field bulk density with the Gupta-Larson model can be done on a routine basis to determine where and when soil compaction is likely to occur. This can be done by making an extra input during determination of particle size distribution, *i.e.* to separate the soil into at least ten particle size classes.

## 7.3 PERSPECTIVE

This study offered the following perspective: Many vineyard soils are exceptionally susceptible to compaction. An understanding of the soil factors influencing compaction is essential for the development of improved soil management practices to increase grapevine performance. The first step towards the control of compaction is prediction. Whereas this goal can be easily stated, accomplishing it is difficult for a number of reasons. First, many different soils impede grapevine root growth at different soil bulk densities. Second, very little is known about the interaction of different chemical, physical and mechanical soil properties. To deny that soil compaction is dependent on intra- and interspecific soil properties, is the same as to deny its very existence. Equally foolhardy is the presumption that individual soil series within a soil form will react the same, they won't even within a specific soil serie. Moreover, any attempt to generalise on the effect of soil texture *per sé* is fraught with difficulty. Nevertheless, as a baseline in soil management, prediction models based on soil textural properties appear to offer considerable initial promise. A narrow interpretation of any classification produced by a model might be dangerous if it is not complemented by practical experience and in *situ* root studies. Such a holistic approach can help to identify soils subjected to compaction problems in the field. With this study, a start at gathering such information has been made. Although refinements are necessary, the concept to use soil texture to classify for compactibility is sound, because it was found to be the most important variable explaining differences in compactibility.

## 7.4 FUTURE RESEARCH

Several directions for future research are suggested by this investigation:

1) The next logical step will be to subject the data to a detailed cluster analysis involving chemical,

physical and clay mineralogical properties.

2) The sample population used in this study can serve as a basis for further studies. For example, soil compressibility studies to describe the soil's behaviour under various stresses are necessary. Furthermore, the sampling sites, of which a substantial amount of quantitative information is available, may serve as modal profiles for benchmarking.

3) The different soil groups identified in this study should be investigated in greater detail. This will be a priority in ongoing compaction research.

4) Soil loosening is an expensive practice in managing soil compaction. Consequently, it is important to determine for different soil types how long such loosening will last, and if it can be maintained long enough to allow an economic return.

5) Further studies on the soil volume/plant available soil water interaction are needed to supply a more definite understanding of the required rooting volume for grapevines.

6) Grapevine root growth limiting bulk densities should be determined under field conditions in order to obtain information on conditions likely to cause root impedance. Threshold values of soil bulk density and penetrometer soil strength that will reduce vine growth significantly must be studied. These values are required to place predicted soil bulk densities in perspective.

7) The ability to perform sensitivity analyses on parameters of the Gupta-Larson model to enable evaluation of the magnitude of different input data, is a research area that has not yet been exploited. Now that preliminary testing has proved the applicability of the model for South African vineyard soil conditions, an in depth study of various combinations between different particle size classes may be done.

Although the various points have been listed separately above, this research will naturally be done as an integral part of and parallel to ongoing compaction research at the V.O.R.I.

"Alice soon came to the conclusion that it was a very difficult game indeed" (Alice in Wonderland).

# APPENDICES

 

Appendix 1. Origin of and general background information on the 71 soils sampled for compaction studies.

| Sample No. | Background information |
|---|---|
| 1 | Lutzville Experimental Farm, Lutzville. Poor growth of the vineyard was due to poor water infiltration through the layer sampled for this study. This alluvial soil was typical of the "sensitive" loamy sands on the river terraces of the Elephants River. This soil was under mechanical clean tillage and flood irrigation for a prolonged period prior to sampling. |
| 2 | Paarl. Uneven growth of the two year old vineyard was due to poor root development in the soil profile, which had three years previously been deep ploughed. This vineyard was under clean tillage. |
| 3 & 4 | Groenberg, Wellington. Low-lying hydromorphic soil which had to be deep ploughed for vineyard due to the high bulk densities in the subsoil. The permanence of the loosening action is often doubtful on such soils. Samples were taken in unloosened soil of this grazeland. |
| 5 | Nietvoorbij Experimental Farm, Stellenbosch. This soil, which developed from Malmesbury shale as parent material, had six years previously been deep ploughed in two directions to a depth of 750 mm. It was limed to approximately pH 5 (1 *M* KCl) before it was planted to a vineyard. Although there was a homogeneous root development throughout the profile, this soil recompacted to high bulk densities under wheel traffic, and a soil crust formed on the surface. The penetrometer readings and soil sample were taken between the wheel tracks. The vineyard is under minimum tillage and is cultivated only once a year to a depth of 50 mm to sow a cover crop. |
| 6-9 | Nietvoorbij Experimental Farm, Stellenbosch. This soil developed from granite and has high bulk densities in the subsoil in the natural state. It has a high percentage of the 2 to 6 mm size fraction. The saprolite underlying this soil was also sampled because this soil type occurs as various depth phases in the Western Cape. Saprolite is very often being loosened by deep tillage prior to the planting of vineyards. The profile that was sampled was ripped to a depth of 500 mm about ten years ago and was since then used for hay - |

Continued on next page)

Appendix 1. Continued.

| Sample No. | Background information |
|---|---|
| | making. The topsoil was relatively loose at the time of sampling because it had been loosened with a disc. It has since been deep ploughed and planted to a vineyard. These soils are known to be stable against "natural" recompaction, but is prone to wheel compaction. |
| 10-13 | Bellevue, Koelenhof (near Stellenbosch). Like the abovementioned soil type, this duplex soil is also very important for grapevine growing in the Western Cape. It also occurs as various depth phases. As the penetrometer soil strength indicated, this soil had relatively high soil strengths in the unloosened state, even at shallow depths, which is the reason why many old vineyards on such soils never reach high production potentials. The E horizon of this soil displayed reversible hardsetting/cementation upon successive drying and wetting cycles. The unloosened soil was sampled, which allowed comparative penetrometer studies on the loosened soil as well as measurement of recompaction due to wheel traffic. |
| 14-16 | Nietvoorbij Experimental Farm, Stellenbosch. Representative of the low-lying, heavy textured, wet and dark coloured hydromorphic soils of the Western Cape. Due to the wetness and structural instability, this soil was ridged before establishment of the vineyard. Because of ridging, the topsoil (Sample no. 14) was loose at the time of sampling . |
| 17 & 18 | Nietvoorbij Experimental Farm, Stellenbosch. Adjacent to the previous soil, but somewhat drier and with lower bulk densities. After the construction of cut-off drains such soil types are usually deep ploughed, but sometimes with doubtful results. The unloosened soil was sampled. |
| 19 | La Bri, Franschhoek. An investigation into the poor and very uneven growth of the six year old vineyard on this soil, which was deep ploughed before planting, showed very shallow root systems in the patches of poor growth, and only occassional deep rooting in the better growing areas. It was not sure whether this soil recompacted on its own or due to wheel traffic. |

(continued on next page)

Appendix 1. Continued.

| Sample No. | Background information |
|---|---|
| 20 | Brackenfell (between Stellenbosch and Cape Town). This regic sand has a tendency towards slight, but reversible, hardsetting upon wetting and drying. |
| 21-33 | Welgevallen Experimental Farm, Stellenbosch. Four adjacent, morphologically distinct, soil profiles within 75 m distance on a sloping foothill were sampled in order to try to determine the effect of soil forming processes, if any, on compactibility of these soils of granitic origin. These soils are known for their high bulk densities and low pH's in the subsoil and are representative of many hectares of similar soil types used for grapevine growing in the Western Cape. This field was never ploughed deeper than 200 mm and had a typical plough pan at approximately 100 mm depth. The surface soil layer had not been loosened for one year prior to sampling. Each of the four profiles is briefly described below: |
| (i) 21-23 | A very deep soil with soil animal activity throughout the profile and relatively homogeneous penetrometer soil strengths with depth. |
| (ii) 24-27 | Also very deep, but with increasing bulk densities and penetrometer soil strengths with depth. |
| (iii) 28-30 | Less well-drained than the two previous profiles, not as deep, and with definite higher compaction in the subsoil. |
| (iv) 31-33 | This soil is during winter subjected to periodic oversaturation due to a perched water table on the very dense B21 horizon. |
| 34 & 35 | Elsenburg Experimental Farm, Muldersvlei (near Stellenbosch). A duplex soil of which the A12 and E horizons show reversible hardening upon wetting and drying. Although of practically the same texture, the Ap horizon does not display such characteristics and also has a lower bulk density. This soil is used for grazing land, was never deep ploughed and the surface soil was not disturbed during the nine months prior to sampling. |

(continued on next page)

Appendix 1. Continued.

| Sample No. | Background information |
|---|---|
| 36-39 | Elsenburg Experimental Farm, Muldersvlei (near Stellenbosch). This undisturbed, deep, well-drained high potential soil has varying densities with depth, which must have been due to natural soil forming processes because sample nos. 38 and 39 practically have the same texture, but sample no. 38 is loose in the natural state. There are definite signs of clay illuviation into the B21 horizon (Sample no. 37). |
| 40 | Elsenburg Experimental Farm, Muldersvlei (near Stellenbosch). Virgin soil which was sampled because of its high 2 to 6 mm size fraction. This soil provided a favourable rooting medium for grapevines. No field bulk density could be obtained due to the high gravel content. |
| 41 | Oudtshoorn Experimental Farm, Oudtshoorn. The topsoil of this alluvial soil is unstable, and it slumps after irrigation when under clean tillage, sets hard upon drying and causes poor water infiltration. |
| 42 & 43 | Slaley, Stellenbosch. This soil had been deep ploughed one year previous to sampling, and is probably unstable because large masses slipped downhill during the winter (not transported by water). This soil becomes very hard upon drying. |
| 44 | Babilonstoren, Klapmuts (near Paarl). This very deep well-drained soil was deep ploughed one year before sampling. It appears to be a stable soil with no compaction problems, not even in the natural state, and was loose when sampled although there was a lot of traffic on it after deep ploughing until the vineyard was planted. |
| 45 | Welmoed, Vlottenburg. This soil was sampled because it had a layer, which impeded grapevine root penetration. This soil had been replanted twice unsuccessfully, each time after deep ploughing. |

(continued on next page)

Appendix 1. Continued.

| Sample No. | Background information |
|---|---|
| 46 | Welmoed, Vlottenburg. Adjacent to the previous soil, but with no root penetration problems. These two soils were sampled because it was expected that the visual textural differences between the two might explain the different rooting patterns. |
| 47 | Neethlingshof, Stellenbosch. This soil recompacted within one year after deep ploughing because it was worked when too wet. Many such soils are being deep ploughed each year at varying soil water contents. |
| 48 | Alphen, Stellenbosch. Virgin soil under natural veld. Many such soils will come under cultivation in near future and it is uncertain whether it will recompact after deep loosening. Very dense in the natural state. |
| 49-52 | Van Zyls Damme, Ladismith. These alluvial soils were sampled because the young vineyard started dying in patches due to shallow roots and poor water infiltration on that particular spots (Sample nos. 49 and 50). Although the differences in growth could not be explained by penetrometer and bulk density studies, the vineyard reacted to deep ripping alongside the rows and the poor spots are picking up. These samples represent a typical situation where it is not possible to predict the problems beforehand, and which is very expensive to rectify once the vineyard has been planted. This vineyard was under clean tillage and flood irrigation, and at the time of sampling received only two irrigations since the topsoil (Sample nos. 49 and 51) had last been loosened. |
| 53 & 54 | Overgaauw, Vlottenburg. This high potential soil was deep ploughed twenty years ago, but only to a depth of 400 mm, and 20 t $ha^{-1}$ manure was applied. The depth at which the plough share cut the soil formed a very effective barrier to root penetration. Large clods also formed due to ineffective tillage at the time. It is expected that this soil is stable to recompaction after loosening. The topsoil does not get particularly hard when dry. |

(continued on next page)

Appendix 1. Continued.

| Sample No. | Background information |
|---|---|
| 55 | Overgaauw, Vlottenburg. This soil was sampled because it did not seem to have compaction problems. |
| 56-58 | Upington Experimental Farm, Upington. The root impeding layers in the profile are generally ascribed to textural differences in this alluvial soils. Alternating soil layers with different textures are a well-known problem in this area, but it is not always recognised that compaction may be the primary problem. |
| 59 | Kromfontein, Ceres. This soil was included in the study for it had a high bulk density in the 150 to 350 mm depth layer, but it is expected that this soil has a stable structure. |
| 60 & 61 | Kromfontein, Ceres. A sharp increase in bulk density was observed at the 250 mm soil depth, accompanied by an increase in penetrometer soil strength. It was uncertain whether it was a ploughpan or natural compaction, and further it was expected that this soil may be very sensitive to recompaction after deep loosening. |
| 62 | Kromfontein, Ceres. This dark coloured organic rich soil is naturally very compact from the 200 mm depth downwards, but this soil will probably remain loose after deep ploughing. |
| 63 | Groenland, Kuilsrivier. The very dense traffic pan at 150 to 350 mm depth impeded grapevine root penetration to the very loose subsoil. |
| 64 | Oudtshoorn. The horizon that was sampled impeded grapevine root penetration and seemed to be unstable due to the relatively high fine sand content. |
| 65 | Paardekloof, Ceres. Unstable topsoil that has been ridged, but which formed a surface crust. This soil had been ridged only three months prior to sampling, and was obviously still very loose underneath the crust. |

(continued on next page)

Appendix 1. Continued.

| Sample No. | Background information |
|---|---|
| 66 | Suiderland, Piketberg. A very shallow (*ca.* 150 mm) root system, with only occassional deep roots. This expectedly unstable soil, which was previously been deep ploughed, caused irrigation management problems. |
| 67 | Koelenhof (near Stellenbosch). This hydromorphic, low-lying soil was ridged because of wetness in the subsoil. The topsoil sets hard when dry and is probably unstable. |
| 68 | Kromfontein, Ceres. Compaction at 70 mm depth due to implement traffic led to poor growth of onions. |
| 69 | Kromfontein, Ceres. Uncompacted profile adjacent to sample no. 68, and which was managed similarly. These two soils were sampled in order to try to explain the observed differences in compaction over short distances. |
| 70 | Kromfontein, Ceres. High potential soil, which, so far, did not give any compaction problems under intensive vegetable growing. |
| 71 | Nietvoorbij Experimental Farm, Stellenbosch. Topsoil of a previous soil preparation trial known to recompact only under wheel traffic. This soil gets very hard when dry and has water run-off problems when under clean tillage. |

Appendix 2. Particle size analysis data (<2 mm diameter basis) for 71 soil samples separated into ten different fractions*

| Sample No. | % of total soil mass per size class | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2,000 to 1,000 mm | 1,000 to 0,500 mm | 0,500 to 0,300 mm | 0,300 to 0,250 mm | 0,250 to 0,106 mm | 0,106 to 0,075 mm | 0,075 to 0,050 mm | 0,050 to 0,020 mm | 0,020 to 0,002 mm | <0,002 mm |
| 1 | 0,04 | 0,23 | 0,90 | 1,60 | 58,31 | 18,05 | 6,54 | 5,97 | 5,80 | 4,44 |
| 2 | 0,41 | 10,30 | 24,14 | 12,07 | 31,99 | 6,11 | 3,12 | 4,01 | 3,28 | 4,94 |
| 3 | 0,35 | 0,67 | 1,86 | 1,95 | 14,38 | 9,88 | 5,34 | 17,18 | 28,93 | 18,51 |
| 4 | 0,69 | 0,67 | 2,64 | 3,07 | 27,94 | 15,67 | 9,68 | 13,21 | 18,11 | 8,45 |
| 5 | 3,24 | 2,72 | 6,37 | 4,53 | 22,33 | 8,99 | 6,02 | 13,05 | 13,17 | 19,67 |
| 6 | 19,92 | 9,18 | 6,32 | 2,48 | 9,81 | 4,04 | 4,37 | 15,04 | 17,32 | 13,39 |
| 7 | 10,08 | 8,73 | 7,11 | 2,21 | 7,73 | 4,00 | 2,97 | 11,45 | 17,04 | 29,47 |
| 8 | 6,99 | 6,68 | 5,41 | 1,92 | 8,21 | 6,08 | 4,10 | 10,05 | 15,14 | 35,75 |
| 9 | 9,24 | 7,20 | 6,70 | 2,26 | 12,30 | 4,65 | 3,81 | 10,60 | 24,27 | 17,60 |
| 10 | 18,92 | 25,51 | 18,14 | 5,48 | 19,16 | 4,05 | 2,69 | 0,40 | 2,02 | 2,42 |
| 11 | 16,80 | 27,11 | 17,87 | 5,37 | 18,14 | 4,56 | 2,43 | 2,37 | 2,77 | 2,41 |
| 12 | 29,18 | 32,70 | 15,19 | 4,12 | 10,21 | 2,57 | 1,43 | 1,66 | 2,11 | 1,20 |
| 13 | 23,21 | 19,15 | 8,90 | 2,60 | 7,97 | 2,38 | 1,32 | 2,18 | 3,82 | 28,06 |
| 14 | 1,30 | 2,42 | 4,41 | 2,39 | 13,75 | 6,99 | 5,52 | 17,63 | 29,02 | 17,56 |
| 15 | 1,06 | 1,90 | 3,64 | 2,83 | 12,99 | 6,77 | 4,77 | 18,77 | 27,80 | 20,56 |
| 16 | 0,46 | 1,25 | 4,51 | 2,68 | 14,09 | 8,11 | 6,35 | 13,24 | 29,35 | 18,62 |
| 17 | 5,69 | 7,94 | 7,77 | 1,85 | 13,92 | 6,63 | 5,76 | 18,51 | 19,08 | 14,66 |
| 18 | 7,13 | 14,99 | 7,92 | 2,30 | 14,00 | 5,68 | 5,73 | 14,94 | 15,83 | 11,52 |
| 19 | 0,99 | 12,85 | 28,37 | 8,99 | 27,79 | 5,33 | 2,59 | 4,41 | 2,67 | 5,79 |
| 20 | 11,39 | 21,35 | 18,89 | 7,53 | 26,27 | 6,01 | 3,20 | 3,73 | 1,26 | 1,17 |
| 21 | 4,21 | 4,77 | 6,32 | 4,07 | 20,24 | 8,40 | 5,13 | 10,37 | 10,59 | 26,61 |
| 22 | 3,69 | 4,80 | 6,08 | 2,90 | 17,23 | 7,20 | 3,99 | 8,75 | 9,56 | 35,57 |
| 23 | 4,01 | 4,18 | 5,62 | 3,31 | 17,75 | 7,37 | 4,85 | 8,99 | 8,14 | 34,71 |
| 24 | 9,17 | 7,34 | 9,04 | 3,80 | 20,32 | 8,82 | 4,23 | 8,59 | 7,52 | 21,44 |
| 25 | 9,14 | 7,85 | 6,37 | 3,34 | 15,63 | 6,92 | 3,32 | 7,17 | 6,08 | 35,32 |

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Appendix 2. Continued.

| Sample No. | % of total soil mass per size class | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2,000 to 1,000 mm | 1,000 to 0,500 mm | 0,500 to 0,300 mm | 0,300 to 0,250 mm | 0,250 to 0,106 mm | 0,106 to 0,075 mm | 0,075 to 0,050 mm | 0,050 to 0,020 mm | 0,020 to 0,002 mm | <0,002 mm |
| 26 | 14,41 | 10,58 | 6,62 | 3,39 | 13,82 | 5,40 | 3,37 | 6,54 | 5,60 | 29,29 |
| 27 | 8,46 | 11,33 | 8,17 | 2,85 | 15,57 | 6,28 | 3,53 | 7,71 | 6,62 | 30,07 |
| 28 | 10,19 | 8,88 | 9,08 | 3,27 | 18,02 | 7,43 | 4,34 | 8,27 | 6,73 | 23,58 |
| 29 | 14,20 | 9,15 | 5,84 | 2,52 | 10,69 | 4,30 | 2,98 | 6,56 | 6,23 | 36,47 |
| 30 | 9,92 | 9,60 | 6,79 | 2,95 | 12,44 | 4,97 | 3,28 | 7,20 | 4,87 | 36,01 |
| 31 | 15,20 | 13,47 | 8,39 | 3,57 | 14,36 | 6,00 | 4,27 | 7,66 | 6,40 | 20,61 |
| 32 | 12,70 | 11,80 | 7,35 | 2,05 | 10,26 | 4,54 | 3,57 | 7,16 | 6,80 | 32,53 |
| 33 | 13,92 | 8,25 | 5,82 | 2,27 | 8,80 | 4,50 | 3,28 | 7,28 | 10,58 | 34,40 |
| 34 | 4,89 | 9,28 | 13,11 | 5,49 | 24,17 | 8,28 | 5,25 | 10,05 | 9,30 | 10,18 |
| 35 | 4,56 | 9,41 | 14,28 | 5,58 | 24,06 | 8,45 | 4,38 | 9,88 | 9,35 | 10,23 |
| 36 | 2,34 | 5,18 | 10,46 | 6,19 | 25,47 | 8,69 | 5,24 | 8,29 | 7,31 | 19,79 |
| 37 | 1,39 | 5,44 | 10,28 | 4,79 | 21,37 | 6,98 | 4,19 | 7,17 | 6,86 | 30,71 |
| 38 | 1,55 | 4,14 | 8,91 | 5,18 | 22,49 | 7,89 | 4,68 | 7,78 | 6.83 | 29,73 |
| 39 | 1,36 | 6,06 | 10,43 | 5,15 | 21,34 | 10,03 | 1,15 | 8,23 | 6,78 | 29,94 |
| 40 | 4,89 | 1,95 | 6,46 | 3,38 | 18,44 | 10,58 | 1,69 | 8,33 | 6,67 | 37,63 |
| 41 | 0,39 | 2,84 | 8,77 | 5,81 | 20,50 | 8,44 | 4,86 | 15,00 | 19,99 | 14,57 |
| 42 | 11,58 | 21,25 | 13,84 | 5,03 | 19,94 | 7,35 | 3,06 | 7,04 | 5,27 | 5,98 |
| 43 | 12,02 | 18,78 | 18,18 | 0,02 | 19,64 | 7,06 | 3,79 | 8,86 | 7,04 | 5,43 |
| 44 | 8,34 | 16,01 | 10,59 | 3,84 | 12,88 | 4,75 | 2,29 | 4,97 | 4,97 | 29,67 |
| 45 | 7,94 | 17,35 | 20,80 | 8,33 | 30,08 | 7,13 | 2,16 | 2,25 | 2,02 | 2,42 |
| 46 | 11,96 | 30,53 | 19,18 | 6,57 | 19,26 | 5,16 | 2,04 | 1,29 | 0,96 | 4,51 |
| 47 | 6,14 | 20,16 | 21,15 | 6,11 | 18,79 | 5,09 | 2,61 | 3,96 | 4,29 | 11,33 |
| 48 | 2,51 | 7,61 | 12,89 | 7,57 | 16,16 | 3,95 | 1,53 | 3,67 | 14,46 | 28,04 |
| 49 | 0,23 | 0,67 | 2,23 | 2,07 | 30,59 | 18,03 | 3,71 | 11,09 | 14,93 | 19,56 |
| 50 | 0,06 | 0,13 | 0,66 | 0,95 | 19,08 | 11,88 | 4,75 | 10,24 | 18,40 | 31,64 |

(continued on next page)

Appendix 2. Continued.

| Sample No. | % of total soil mass per size class | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2,000 to 1,000 mm | 1,000 to 0,500 mm | 0,500 to 0,300 mm | 0,300 to 0,250 mm | 0,250 to 0,106 mm | 0,106 to 0,075 mm | 0,075 to 0,050 mm | 0,050 to 0,020 mm | 0,020 to 0,002 mm | <0,002 mm |
| 51 | 0,16 | 0,20 | 0,96 | 1,67 | 34,09 | 20,06 | 6,15 | 14,34 | 12,28 | 13,42 |
| 52 | 0,27 | 0,13 | 0,86 | 1,24 | 24,33 | 14,78 | 4,85 | 9,24 | 15,69 | 27,84 |
| 53 | 9,53 | 8,35 | 12,22 | 5,45 | 23,91 | 6,96 | 3,08 | 5,38 | 11,22 | 12,72 |
| 54 | 8,45 | 15,97 | 12,99 | 8,33 | 25,06 | 6,44 | 3,25 | 4,17 | 2,39 | 16,29 |
| 55 | 13,49 | 12,00 | 17,25 | 8,13 | 24,61 | 6,00 | 3,38 | 4,69 | 4,01 | 7,71 |
| 56 | 0,17 | 0,35 | 0,50 | 0,30 | 5,02 | 23,61 | 20,47 | 29,93 | 9,60 | 12,71 |
| 57 | 0,21 | 0,19 | 0,36 | 0,29 | 9,70 | 31,19 | 13,29 | 27,85 | 7,89 | 9,97 |
| 58 | 0,11 | 0,14 | 0,89 | 0,02 | 23,10 | 26,94 | 11,70 | 18,44 | 7,67 | 11,60 |
| 59 | 3,23 | 3,74 | 4,52 | 3,34 | 20,40 | 16,49 | 7,27 | 14,89 | 12,81 | 17,73 |
| 60 | 0,96 | 1,84 | 3,77 | 2,74 | 32,25 | 27,17 | 8,51 | 10,03 | 4,11 | 11,78 |
| 61 | 0,96 | 1,07 | 3,59 | 2,39 | 32,60 | 26,83 | 7,48 | 10,52 | 5,25 | 13,13 |
| 62 | 8,43 | 37,52 | 18,67 | 4,63 | 10,23 | 3,56 | 3,32 | 6,71 | 4,51 | 6,30 |
| 63 | 17,50 | 23,44 | 14,48 | 5,43 | 19,67 | 4,40 | 2,76 | 3,21 | 5,33 | 5,47 |
| 64 | 0,42 | 4,73 | 19,09 | 13,22 | 34,31 | 6,56 | 3,77 | 6,89 | 5,89 | 6,70 |
| 65 | 0,28 | 1,00 | 2,96 | 2,13 | 37,75 | 8,73 | 4,71 | 10,98 | 14,06 | 15,78 |
| 66 | 4,64 | 18,73 | 20,20 | 6,85 | 21,97 | 5,19 | 4,23 | 8,09 | 7,16 | 5,14 |
| 67 | 2,46 | 11,13 | 9,60 | 3,36 | 16,79 | 6,05 | 4,72 | 7,99 | 7,87 | 29,52 |
| 68 | 13,44 | 53,95 | 9,47 | 3,20 | 7,25 | 2,40 | 1,58 | 2,70 | 2,22 | 5,25 |
| 69 | 21,02 | 48,46 | 11,48 | 2,97 | 5,09 | 2,02 | 1,86 | 2,83 | 1,11 | 4,55 |
| 70 | 7,86 | 14,49 | 11,75 | 5,14 | 20,40 | 8,52 | 4,87 | 9,99 | 10,62 | 8,49 |
| 71 | 3,78 | 4,84 | 4,21 | 2,08 | 17,50 | 11,10 | 7,49 | 16,37 | 12,10 | 21,24 |

*FR1 = 2,00-1,00 mm } Coarse sand
FR2 = 1,00-0,50 mm }
FR3 = 0,50-0,30 mm } Medium sand
FR4 = 0,30-0,25 mm }
FR5 = 0,25-0,106 mm — Fine sand
FR6 = 0,106-0,075 mm } Very fine sand
FR7 = 0,075-0,053 mm }
FR8 = 0,053-0,020 mm — Coarse silt
FR9 = 0,020-0,002 mm — Fine silt
FR10 = <0,002 mm — Clay

Appendix 3. Particle size analysis data (<6 mm diameter basis) for 71 soil samples separated into eleven different fractions.*

| Sample No. | % of total soil mass per size class | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 6,000 to 2,000 mm | 2,000 to 1,000 mm | 1,000 to 0,500 mm | 0,500 to 0,300 mm | 0,300 to 0,250 mm | 0,250 to 0,106 mm | 0,106 to 0,075 mm | 0,075 to 0,050 mm | 0,050 to 0,020 mm | 0,020 to 0,002 mm | <0,002 mm |
| 1 | 0,000 | 0,04 | 0,23 | 0,90 | 1,60 | 58,31 | 18,05 | 6,54 | 5,97 | 5,80 | 4,44 |
| 2 | 0,00 | 0,41 | 10,30 | 24,14 | 12,07 | 31,99 | 6,11 | 3,12 | 4,01 | 3,28 | 4,94 |
| 3 | 1,89 | 0,34 | 0,66 | 1,82 | 1,91 | 14,11 | 9,69 | 5,24 | 16,86 | 28,38 | 18,16 |
| 4 | 0,94 | 0,68 | 0,66 | 2,62 | 3,04 | 27,68 | 15,52 | 9,59 | 13,09 | 17,94 | 8,37 |
| 5 | 20,13 | 2,59 | 2,17 | 5,09 | 3,62 | 17,83 | 7,18 | 4,81 | 10,42 | 10,52 | 15,71 |
| 6 | 47,13 | 10,53 | 4,85 | 3,34 | 1,31 | 5,19 | 2,14 | 2,31 | 7,95 | 9,16 | 7,08 |
| 7 | 27,26 | 7,33 | 6,35 | 5,17 | 1,61 | 5,62 | 2,91 | 2,16 | 8,33 | 12,39 | 21,44 |
| 8 | 15,68 | 5,89 | 5,63 | 4,56 | 1,62 | 6,92 | 5,13 | 3,46 | 8,47 | 12,77 | 30,14 |
| 9 | 13,68 | 7,98 | 6,22 | 5,78 | 1,95 | 10,62 | 4,01 | 3,29 | 9,15 | 20,95 | 15,19 |
| 10 | 5,57 | 17,87 | 24,09 | 17,13 | 5,17 | 18,09 | 3,82 | 2,54 | 0,38 | 1,91 | 2,29 |
| 11 | 4,53 | 16,04 | 25,88 | 17,06 | 5,13 | 17,32 | 4,35 | 2,32 | 2,26 | 2,64 | 2,30 |
| 12 | 8,40 | 26,73 | 29,95 | 13,91 | 3,77 | 9,35 | 2,35 | 1,31 | 1,52 | 1,93 | 1,10 |
| 13 | 6,68 | 21,66 | 17,87 | 8,31 | 2,43 | 7,44 | 2,22 | 1,23 | 2,03 | 3,56 | 26,19 |
| 14 | 2,19 | 1,27 | 2,37 | 4,31 | 2,34 | 13,45 | 6,84 | 5,40 | 17,24 | 28,38 | 17,18 |
| 15 | 1,64 | 1,04 | 1,87 | 3,58 | 2,78 | 12,78 | 6,66 | 4,69 | 18,46 | 27,34 | 20,22 |
| 16 | 0,15 | 0,46 | 1,25 | 4,50 | 2,68 | 14,07 | 8,10 | 6,34 | 13,22 | 29,31 | 18,59 |
| 17 | 10,68 | 5,08 | 7,09 | 6,94 | 1,65 | 12,43 | 5,92 | 5,14 | 16,53 | 17,04 | 13,09 |
| 18 | 14,29 | 6,11 | 12,85 | 6,79 | 1,97 | 12,00 | 4,87 | 4,91 | 12,81 | 13,57 | 9,87 |
| 19 | 0,00 | 0,99 | 12,85 | 28,37 | 8,99 | 27,79 | 5,33 | 2,59 | 4,41 | 2,67 | 5,79 |
| 20 | 3,65 | 10,97 | 20,57 | 18,20 | 7,26 | 25,31 | 5,79 | 3,08 | 3,59 | 1,21 | 1,13 |
| 21 | 2,85 | 4,09 | 4,63 | 6,14 | 3,95 | 19,66 | 8,16 | 4,98 | 10,07 | 10,29 | 25,85 |
| 22 | 2,53 | 3,60 | 4,68 | 5,93 | 2,83 | 16,79 | 7,02 | 3,89 | 8,53 | 9,32 | 34,67 |
| 23 | 2,12 | 3,92 | 4,09 | 5,50 | 3,24 | 17,37 | 7,21 | 4,75 | 8,80 | 7,97 | 33,97 |
| 24 | 4,66 | 8,74 | 7,00 | 8,62 | 3,62 | 19,37 | 8,41 | 4,03 | 8,19 | 7,17 | 20,44 |
| 25 | 4,67 | 8,71 | 7,48 | 6,07 | 3,18 | 14,90 | 6,60 | 3,16 | 6,84 | 5,80 | 33,67 |

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Appendix 3. Continued.

| Sample No. | % of total soil mass per size class | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 6,000 to 2,000 mm | 2,000 to 1,000 mm | 1,000 to 0,500 mm | 0,500 to 0,300 mm | 0,300 to 0,250 mm | 0,250 to 0,106 mm | 0,106 to 0,075 mm | 0,075 to 0,050 mm | 0,050 to 0,020 mm | 0,020 to 0,002 mm | <0,002 mm |
| 26 | 34,33 | 9,46 | 6,95 | 4,35 | 2,23 | 9,08 | 3,55 | 2,21 | 4,29 | 3,68 | 19,23 |
| 27 | 19,62 | 6,80 | 9,11 | 6,57 | 2,29 | 12,52 | 5,05 | 2,84 | 6,20 | 5,32 | 24,17 |
| 28 | 15,57 | 8,60 | 7,50 | 7,67 | 2,76 | 15,21 | 6,27 | 3,66 | 6,98 | 5,68 | 19,91 |
| 29 | 33,63 | 9,42 | 6,07 | 3,88 | 1,67 | 7,09 | 2,85 | 1,98 | 4,35 | 4,13 | 24,21 |
| 30 | 11,96 | 8,73 | 8,45 | 5,98 | 2,60 | 10,95 | 4,38 | 2,89 | 6,34 | 4,29 | 31,70 |
| 31 | 28,74 | 10,83 | 9,60 | 5,98 | 2,54 | 10,23 | 4,28 | 3,04 | 5,46 | 4,56 | 14,69 |
| 32 | 14,67 | 10,84 | 10,07 | 6,27 | 1,75 | 8,75 | 3,87 | 3,05 | 6,11 | 5,80 | 27,76 |
| 33 | 14,99 | 11,83 | 7,01 | 4,95 | 1,93 | 7,48 | 3,83 | 2,79 | 6,19 | 8,99 | 29,24 |
| 34 | 1,51 | 4,82 | 9,14 | 12,91 | 5,41 | 23,81 | 8,15 | 5,17 | 9,90 | 9,16 | 10,03 |
| 35 | 2,19 | 4,46 | 9,20 | 13,97 | 5,46 | 23,53 | 8,26 | 4,28 | 9,66 | 9,15 | 10,01 |
| 36 | 0,55 | 2,33 | 5,15 | 10,40 | 6,16 | 25,33 | 8,64 | 5,21 | 8,24 | 7,27 | 19,68 |
| 37 | 0,22 | 1,39 | 5,43 | 10,26 | 4,78 | 21,32 | 6,96 | 4,18 | 7,15 | 6,84 | 30,64 |
| 38 | 0,62 | 1,54 | 4,11 | 8,85 | 5,15 | 22,35 | 7,84 | 4,65 | 7,73 | 6,79 | 29,55 |
| 39 | 0,85 | 1,35 | 6,01 | 10,34 | 5,11 | 21,16 | 9,94 | 1,14 | 8,16 | 6,72 | 29,69 |
| 40 | 61,95 | 1,86 | 0,74 | 2,46 | 1,29 | 7,02 | 4,03 | 0,64 | 3,17 | 2,54 | 14,32 |
| 41 | 0,00 | 0,39 | 2,84 | 8,77 | 5,81 | 20,50 | 8,44 | 4,86 | 15,00 | 19,99 | 14,57 |
| 42 | 5,99 | 10,89 | 19,98 | 13,01 | 4,73 | 18,75 | 6,91 | 2,88 | 6,62 | 4,95 | 5,62 |
| 43 | 4,51 | 11,48 | 17,93 | 17,36 | 0,02 | 18,75 | 6,74 | 3,62 | 8,46 | 6,72 | 5,19 |
| 44 | 1,72 | 8,20 | 15,73 | 10,41 | 3,77 | 12,66 | 4,67 | 2,25 | 4,88 | 4,88 | 29,16 |
| 45 | 1,56 | 7,82 | 17,08 | 20,48 | 8,20 | 29,61 | 7,02 | 2,13 | 2,21 | 1,99 | 2,38 |
| 46 | 12,99 | 11,60 | 29,62 | 18,61 | 6,37 | 18,68 | 5,01 | 1,98 | 1,25 | 0,93 | 4,38 |
| 47 | 3,11 | 5,95 | 19,53 | 20,49 | 5,92 | 18,21 | 4,93 | 2,53 | 3,84 | 4,16 | 10,98 |
| 48 | 1,07 | 2,48 | 7,53 | 12,75 | 7,49 | 15,99 | 3,91 | 1,51 | 3,63 | 14,31 | 27,74 |
| 49 | 0,38 | 0,23 | 0,67 | 2,22 | 2,06 | 30,47 | 17,96 | 3,70 | 11,05 | 14,87 | 19,49 |
| 50 | 0,00 | 0,06 | 0,13 | 0,66 | 0,95 | 19,08 | 11,88 | 4,75 | 10,24 | 18,40 | 31,64 |

(continued on next page)

Appendix 3. Continued.

| Sample No. | % of total soil mass per size class | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 6,000 to 2,000 mm | 2,000 to 1,000 mm | 1,000 to 0,500 mm | 0,500 to 0,300 mm | 0,300 to 0,250 mm | 0,250 to 0,106 mm | 0,106 to 0,075 mm | 0,075 to 0,050 mm | 0,050 to 0,020 mm | 0,020 to 0,002 mm | <0,002 mm |
| 51 | 0,00 | 0,16 | 0,20 | 0,96 | 1,67 | 34,09 | 20,06 | 6,15 | 14,34 | 12,28 | 13,42 |
| 52 | 0,00 | 0,27 | 0,13 | 0,86 | 1,24 | 24,33 | 14,78 | 4,85 | 9,24 | 15,69 | 27,84 |
| 53 | 4,55 | 9,10 | 7,97 | 11,66 | 5,20 | 22,82 | 6,64 | 2,94 | 5,14 | 10,71 | 12,14 |
| 54 | 2,30 | 8,26 | 15,60 | 12,69 | 8,14 | 24,48 | 6,29 | 3,18 | 4,07 | 2,34 | 15,92 |
| 55 | 4,95 | 12,82 | 11,41 | 16,40 | 7,73 | 23,39 | 5,70 | 3,21 | 4,46 | 3,81 | 7,33 |
| 56 | 4,95 | 0,17 | 0,35 | 0,50 | 0,30 | 5,02 | 23,61 | 20,47 | 29,93 | 9,60 | 12,71 |
| 57 | 0,00 | 0,21 | 0,19 | 0,36 | 0,29 | 9,70 | 31,19 | 13,29 | 27,85 | 7,89 | 9,97 |
| 58 | 0,00 | 0,11 | 0,14 | 0,89 | 0,02 | 23,10 | 26,94 | 11,70 | 18,44 | 7,67 | 11,60 |
| 59 | 10,61 | 2,89 | 3,34 | 4,04 | 2,99 | 18,24 | 14,74 | 6,50 | 13,31 | 11,45 | 15,85 |
| 60 | 0,00 | 0,96 | 1,84 | 3,77 | 2,74 | 32,25 | 27,17 | 8,51 | 10,03 | 4,11 | 11,78 |
| 61 | 1,14 | 0,95 | 1,06 | 3,55 | 2,36 | 32,23 | 26,52 | 7,39 | 10,40 | 5,19 | 12,98 |
| 62 | 0,78 | 8,36 | 37,23 | 18,52 | 4,59 | 10,15 | 3,53 | 3,29 | 6,66 | 4,47 | 6,25 |
| 63 | 5,17 | 16,60 | 22,23 | 13,73 | 5,15 | 18,65 | 4,17 | 2,62 | 3,04 | 5,05 | 5,19 |
| 64 | 0,15 | 0,42 | 4,72 | 19,06 | 13,20 | 34,26 | 6,55 | 3,76 | 6,88 | 5,88 | 6,69 |
| 65 | 2,30 | 0,27 | 0,98 | 2,89 | 2,08 | 36,88 | 8,53 | 4,60 | 10,73 | 13,74 | 15,42 |
| 66 | 4,96 | 4,41 | 17,80 | 19,20 | 6,51 | 20,88 | 4,93 | 4,02 | 7,69 | 6,80 | 4,89 |
| 67 | 1,05 | 2,43 | 11,01 | 9,50 | 3,32 | 16,61 | 5,99 | 4,67 | 7,91 | 7,79 | 29,21 |
| 68 | 1,19 | 13,28 | 53,31 | 9,36 | 3,16 | 7,16 | 2,37 | 1,56 | 2,67 | 2,19 | 5,19 |
| 69 | 2,49 | 20,50 | 47,25 | 11,19 | 2,90 | 4,96 | 1,97 | 1,81 | 2,76 | 1,08 | 4,44 |
| 70 | 1,49 | 7,74 | 14,27 | 11,57 | 5,06 | 20,10 | 8,39 | 4,80 | 9,84 | 10,46 | 8,36 |
| 71 | 4,25 | 3,62 | 4,63 | 4,03 | 1,99 | 16,76 | 10,63 | 7,17 | 15,67 | 11,59 | 20,34 |

*FR16 = 2,00-1,00 mm } Coarse sand
FR26 = 1,00-0,50 mm }
FR36 = 0,50-0,30 mm } Medium sand
FR46 = 0,30-0,25 mm }
FR56 = 0,25-0,106 mm — Fine sand

FR66 = 0,106-0,075 mm } Very fine sand
FR76 = 0,075-0,053 mm }
FR86 = 0,053-0,020 mm — Coarse silt
FR96 = 0,020-0,002 mm — Fine silt
FR106 = <0,002 mm — Clay

Appendix 4. Cumulative frequency curves for particle size analysis data of 71 different soil samples used in a compaction study.

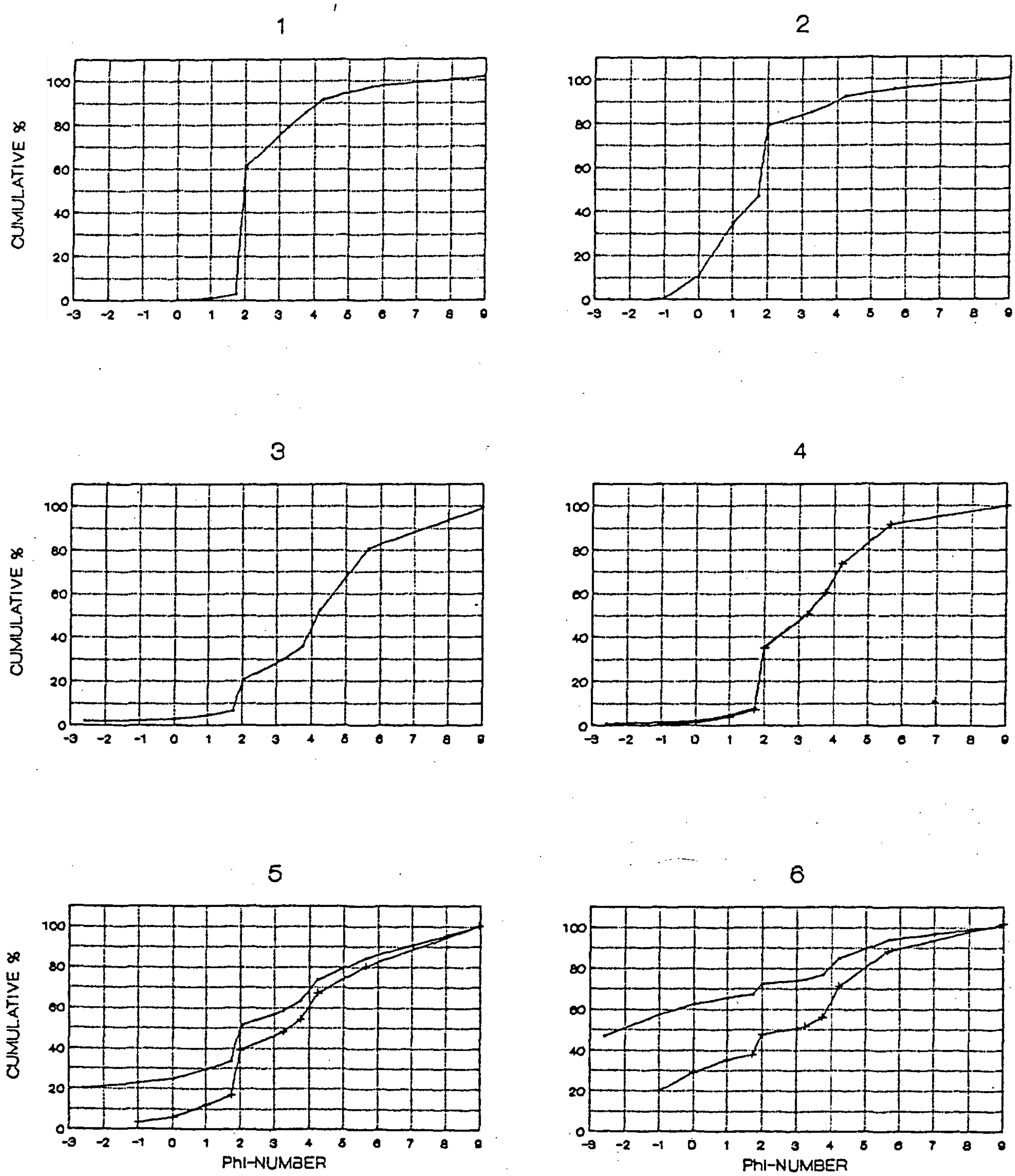


Fig. A.1. Cumulative percentage for the different particle size classes, plotted on the phi-scale, for 71 soil samples used in a compaction study (Lower line = <2 mm diameter basis; Upper line = <6 mm diameter basis). The number above each figure refers to the sample number.

(continued on next page)

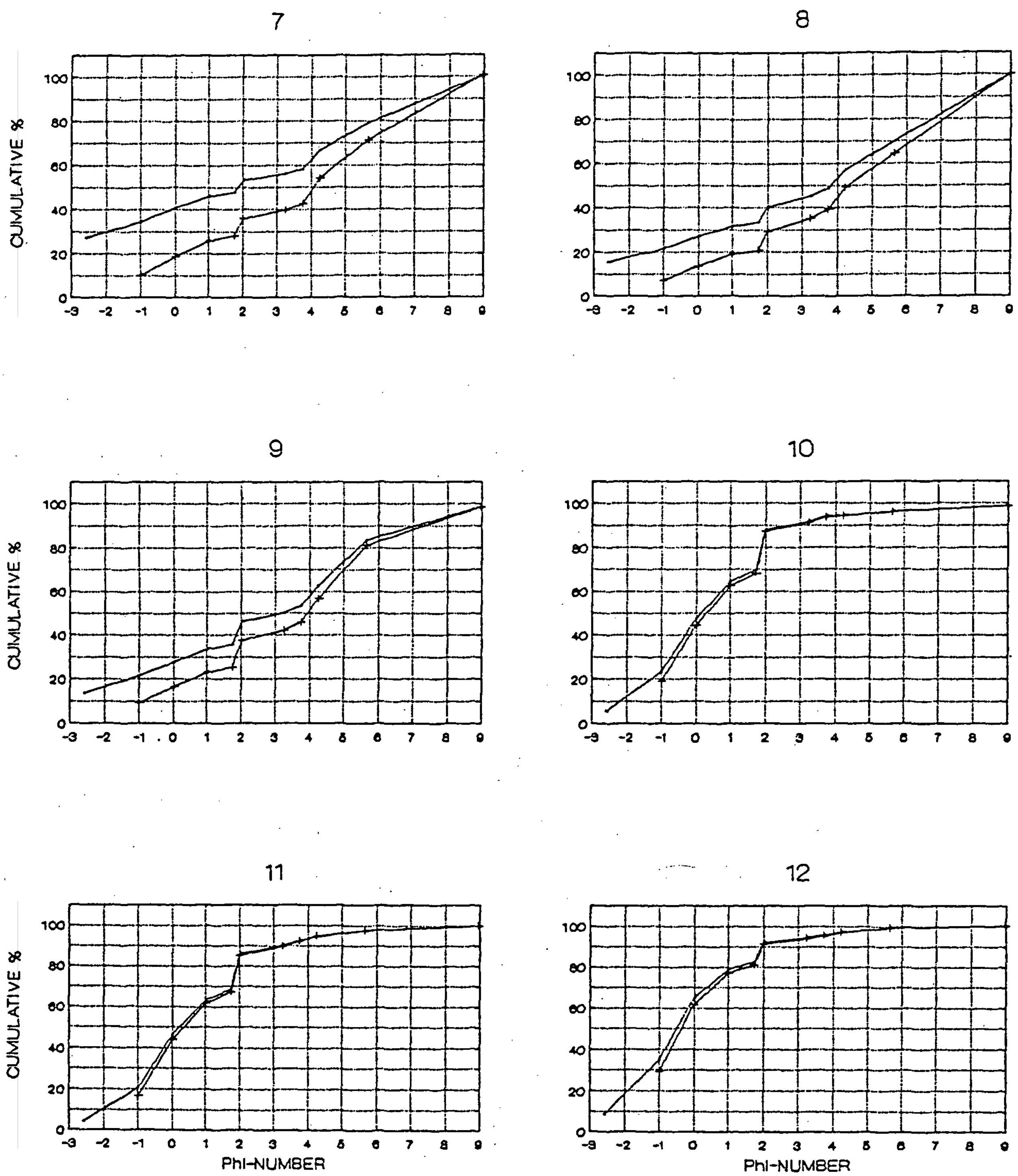


Fig. A.1. Continued.

(continued on next page)

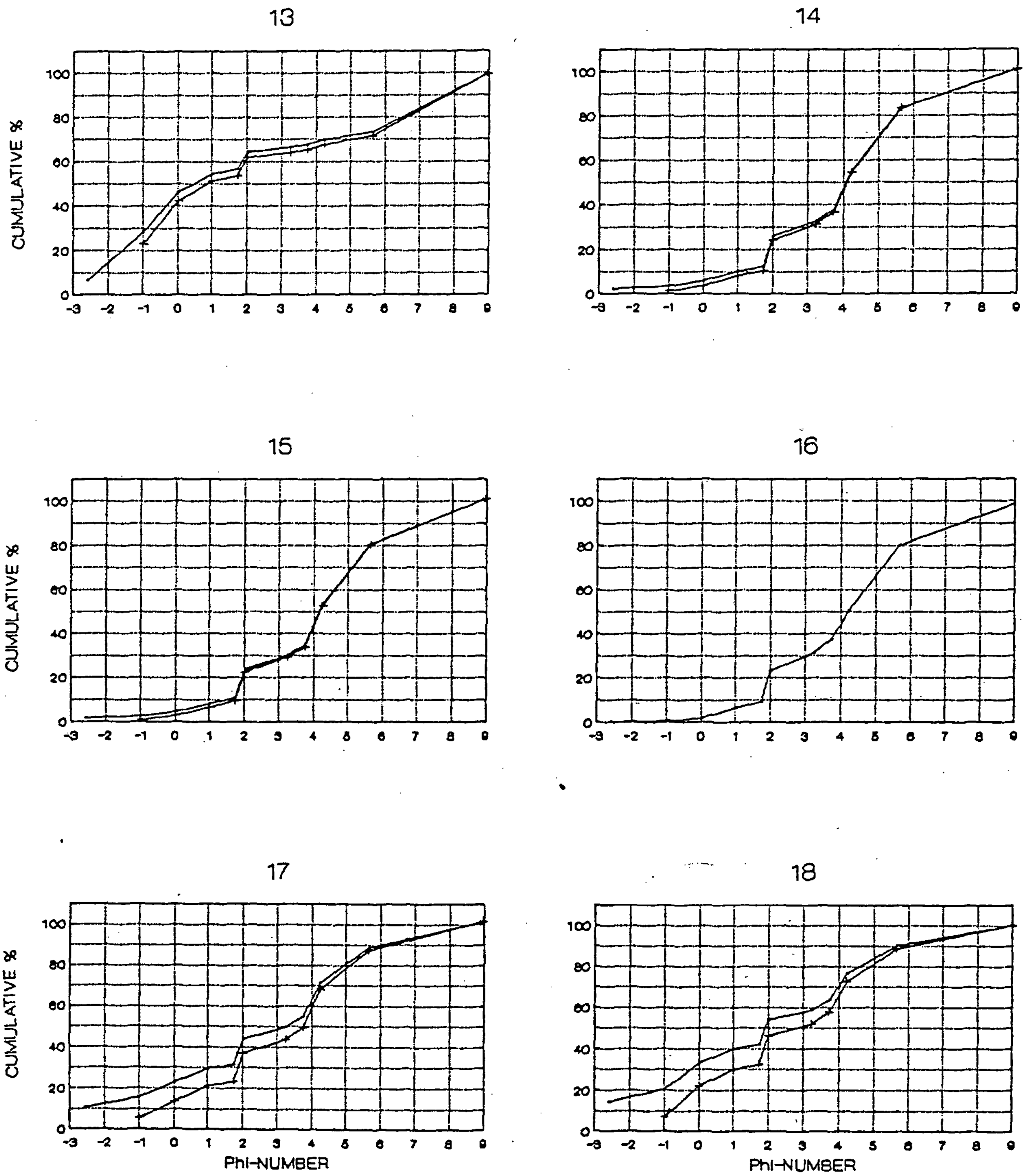


Fig. A.1. Continued.

(continued on next page)

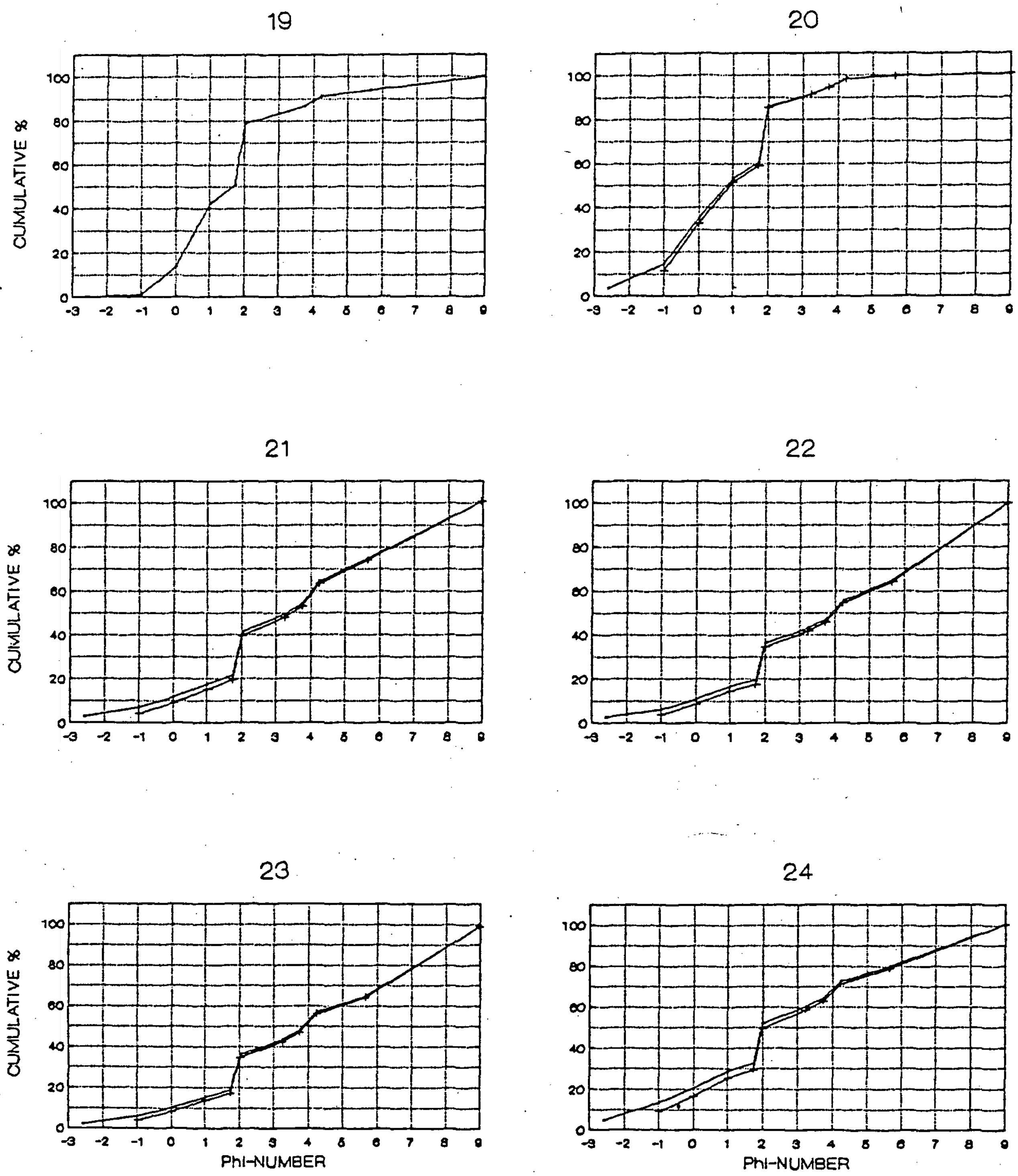


Fig. A.1. Continued.

(continued on next page)

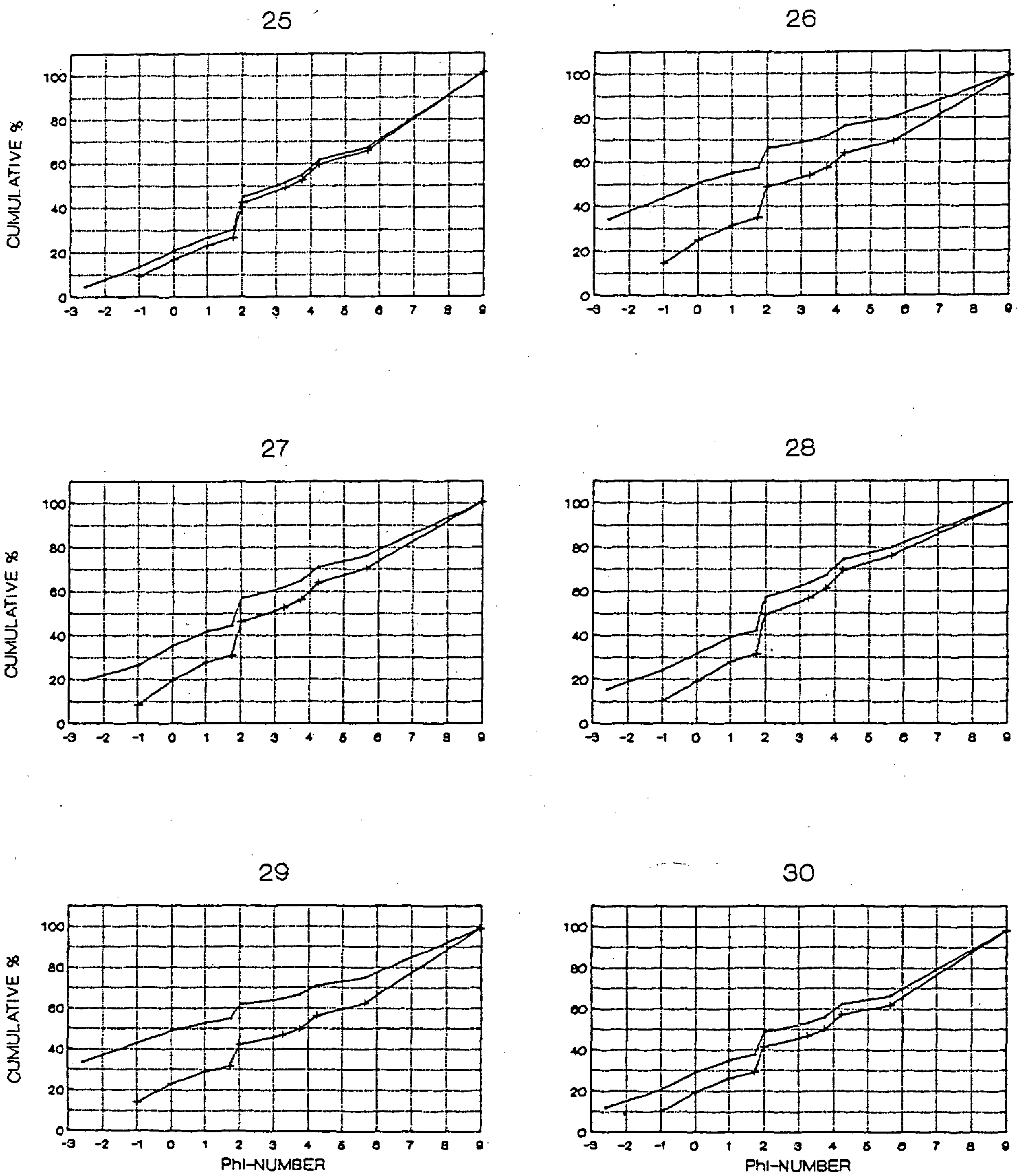


Fig. A.1. Continued.

(continued on next page)

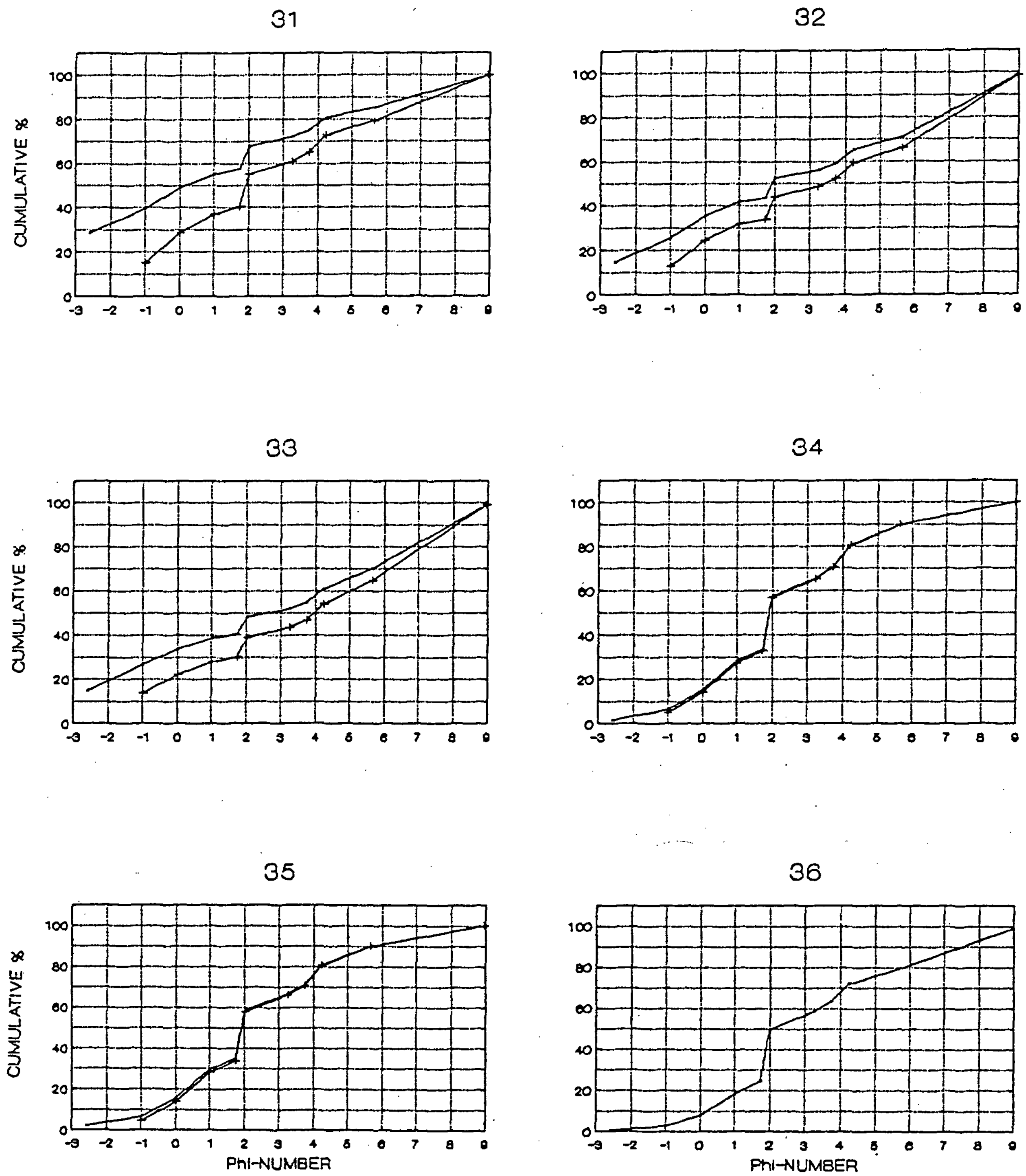


Fig. A.1. Continued.

(continued on next page)

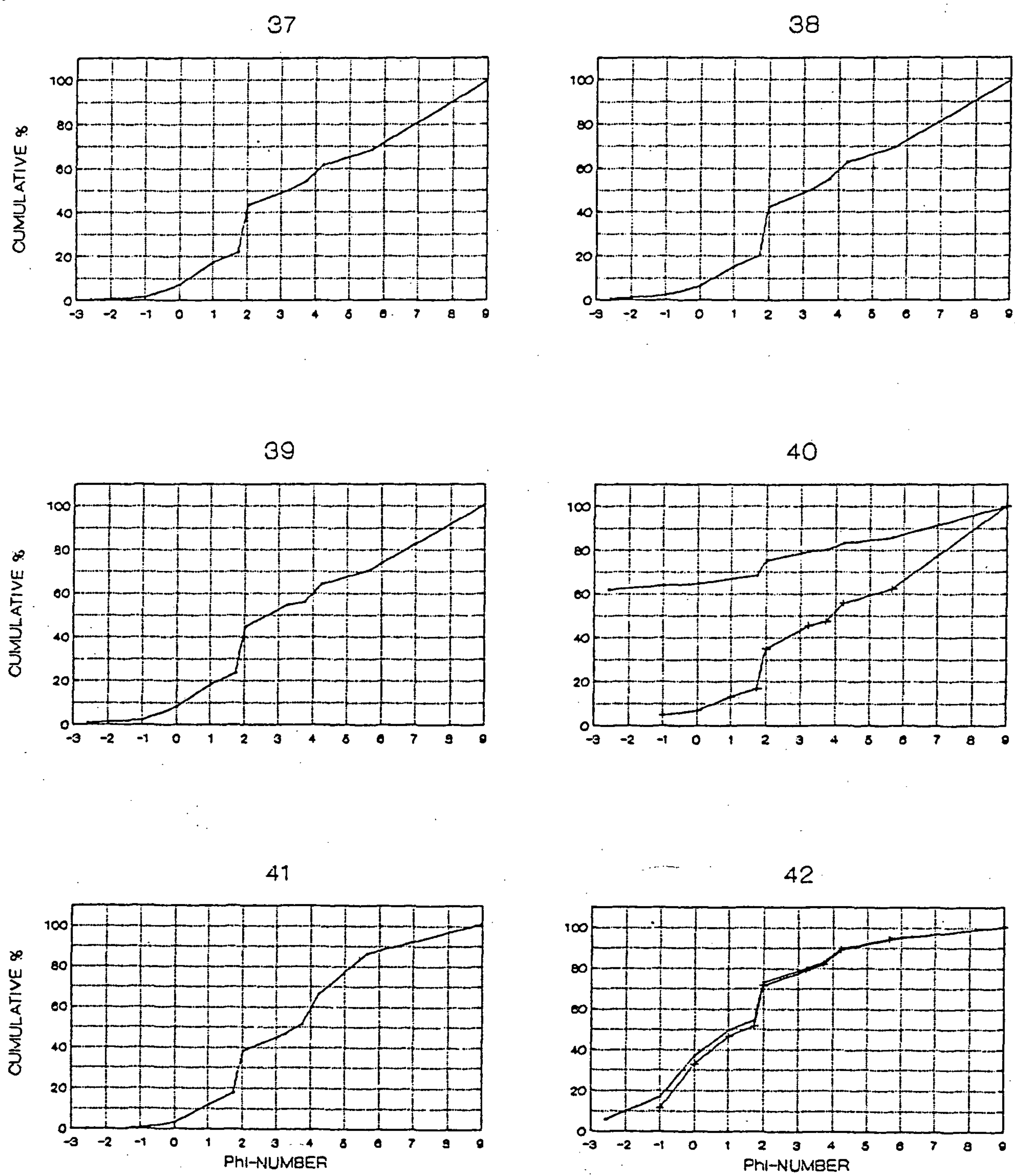


Fig. A.1. Continued.

(continued on next page)

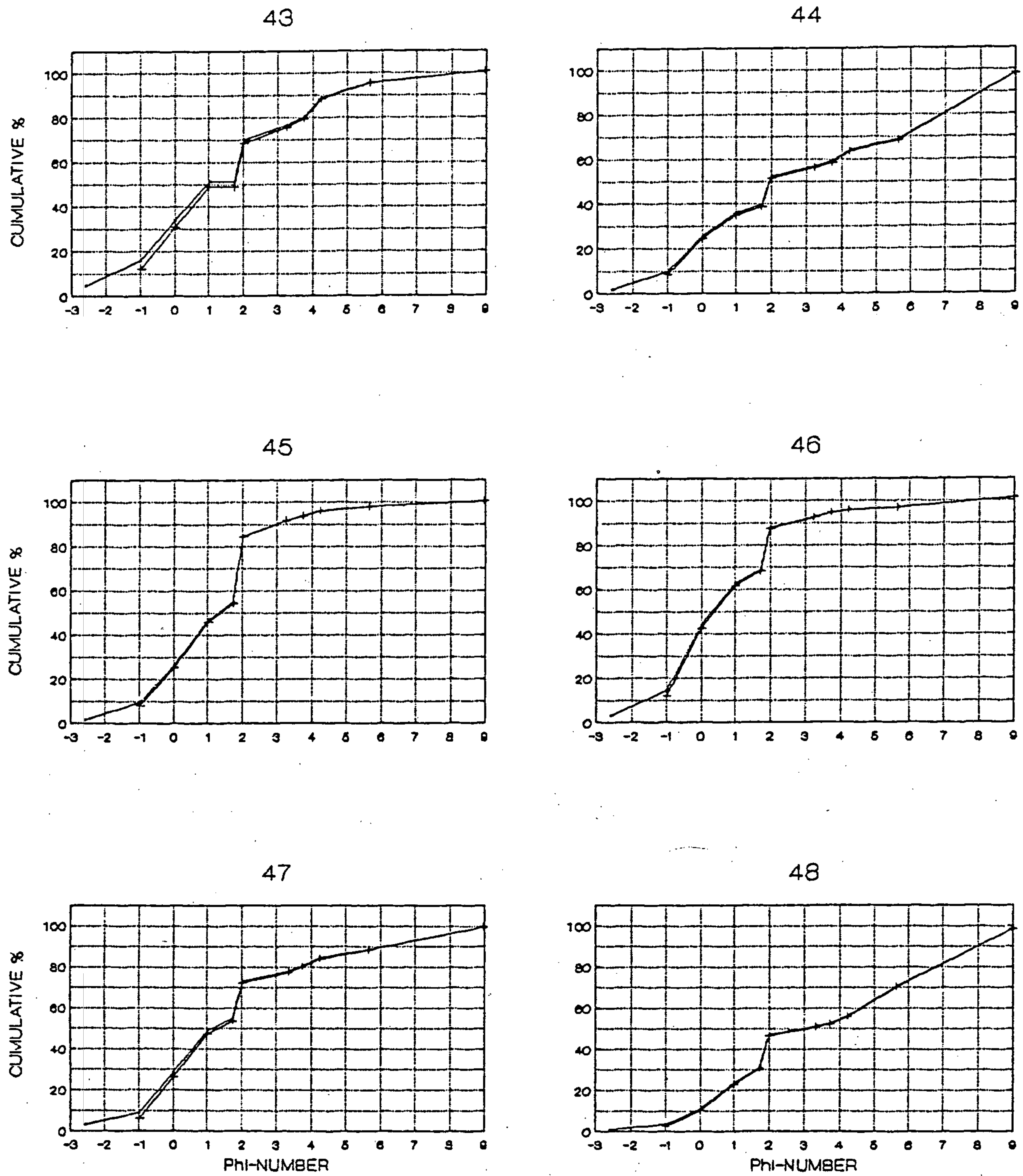


Fig. A.1. Continued.

(continued on next page)

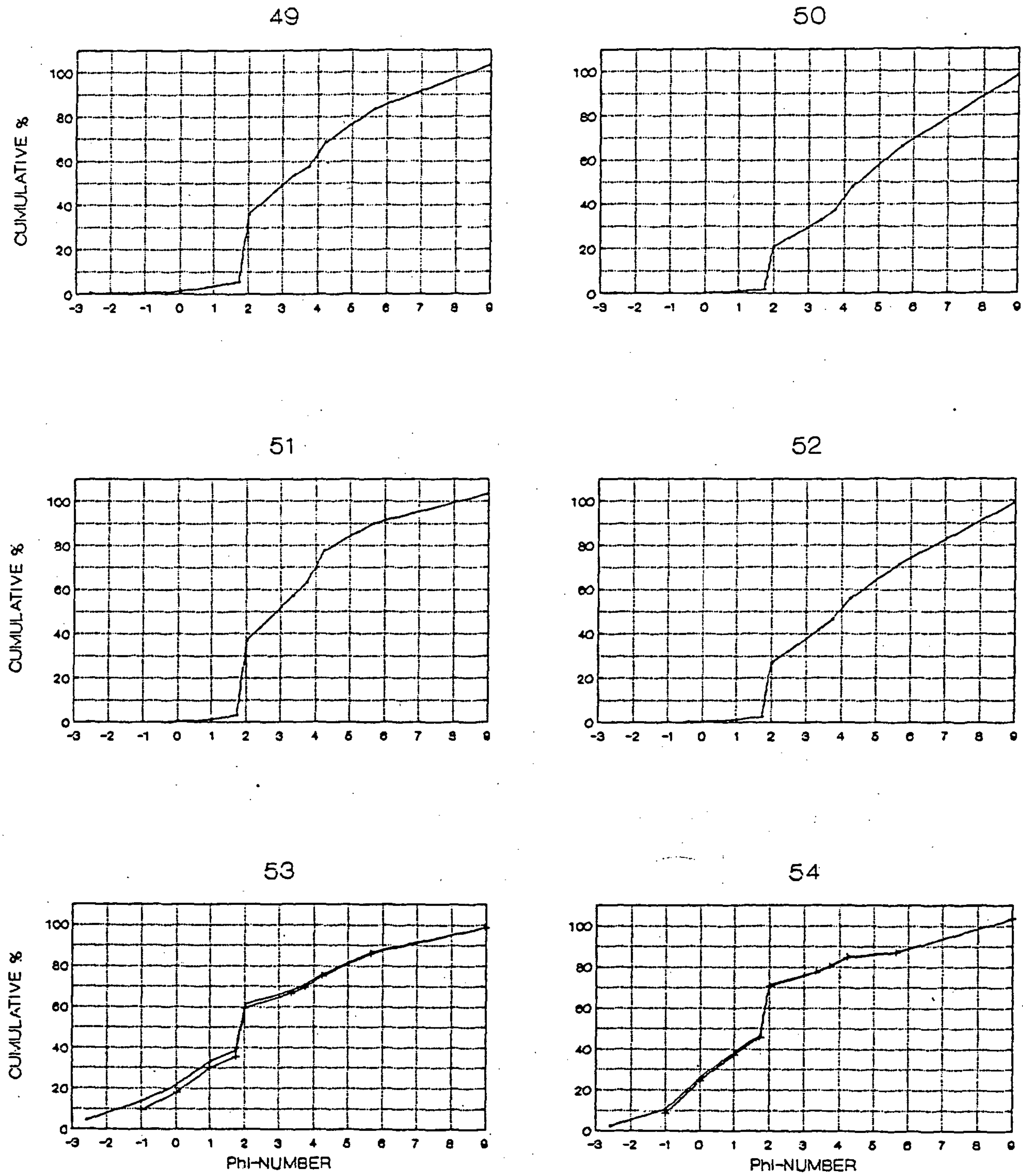


Fig. A.1. Continued.

(continued on next page)

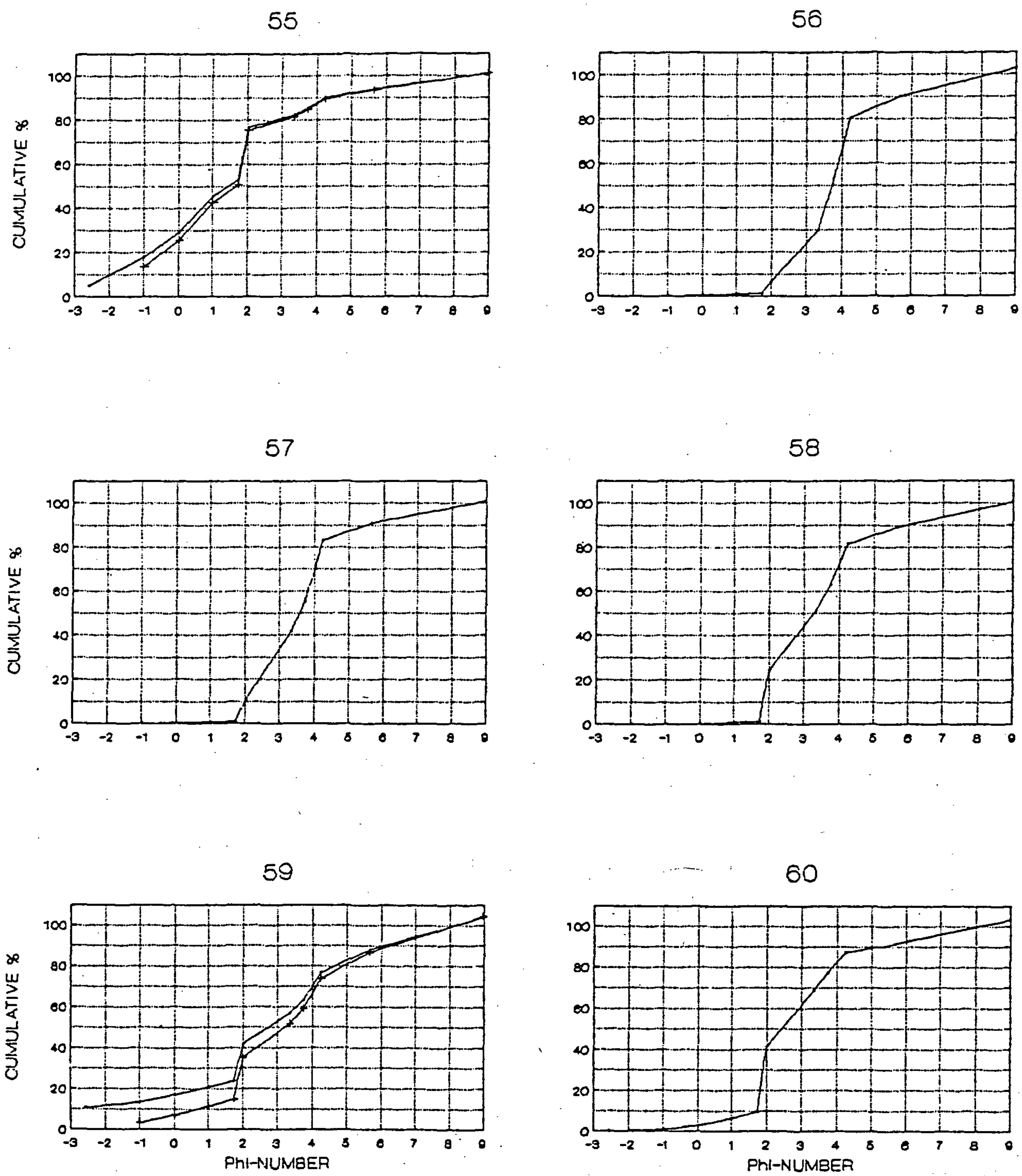


Fig. A.1. Continued.

(continued on next page)

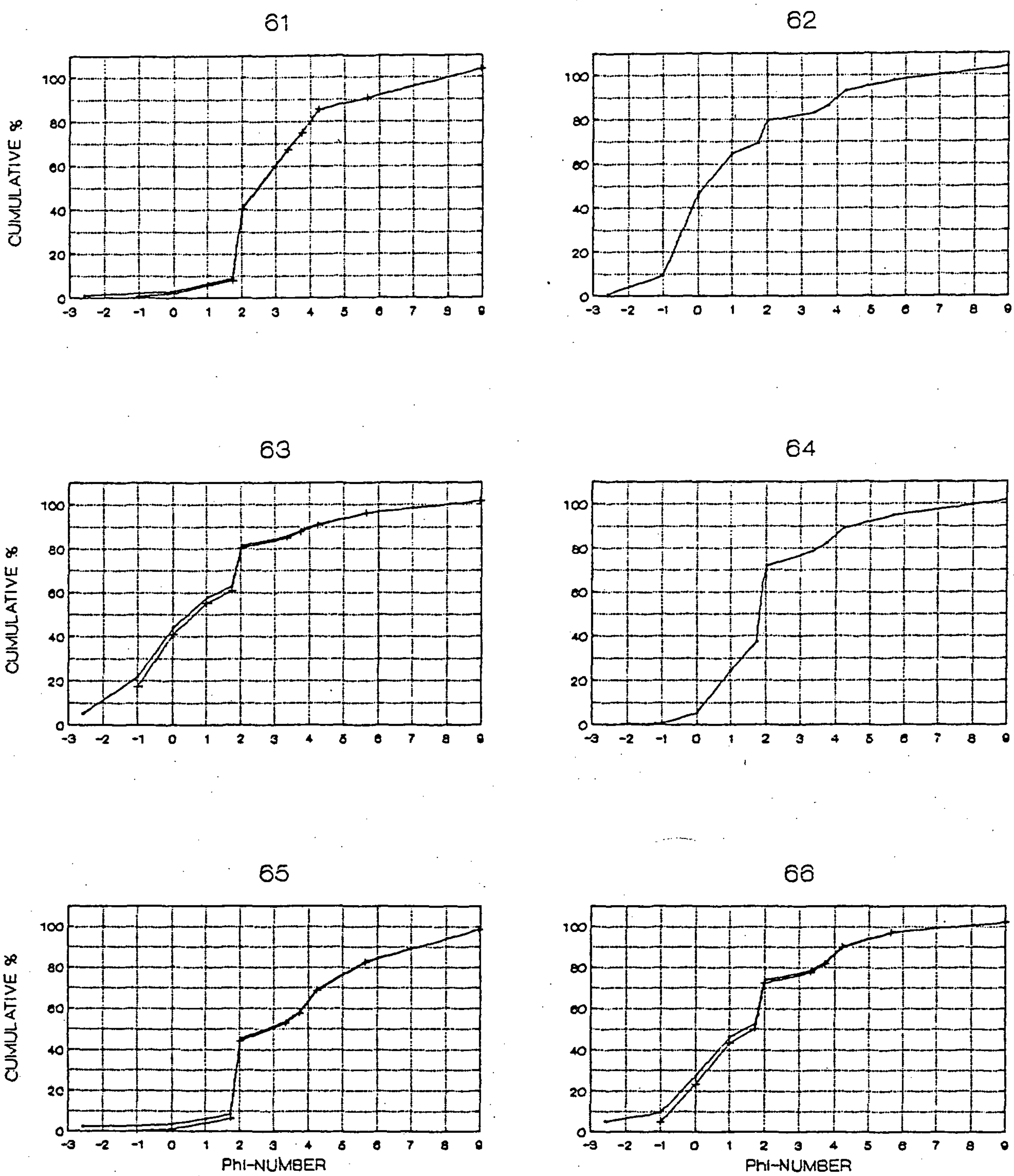


Fig. A.1. Continued.

(continued on next page)

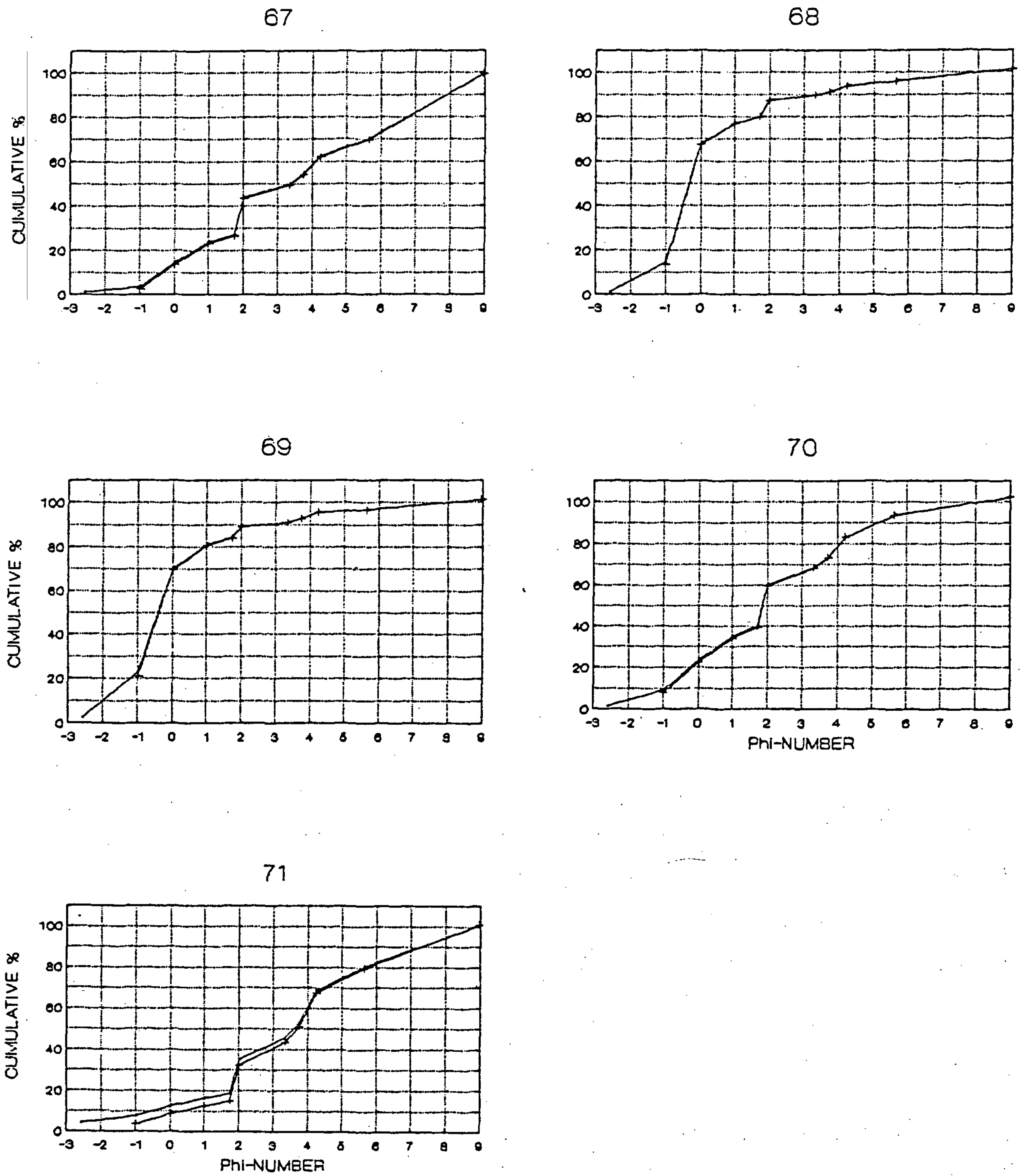


Fig. A.1. Continued.

Appendix 5. Results of Proctor maximum compaction tests.

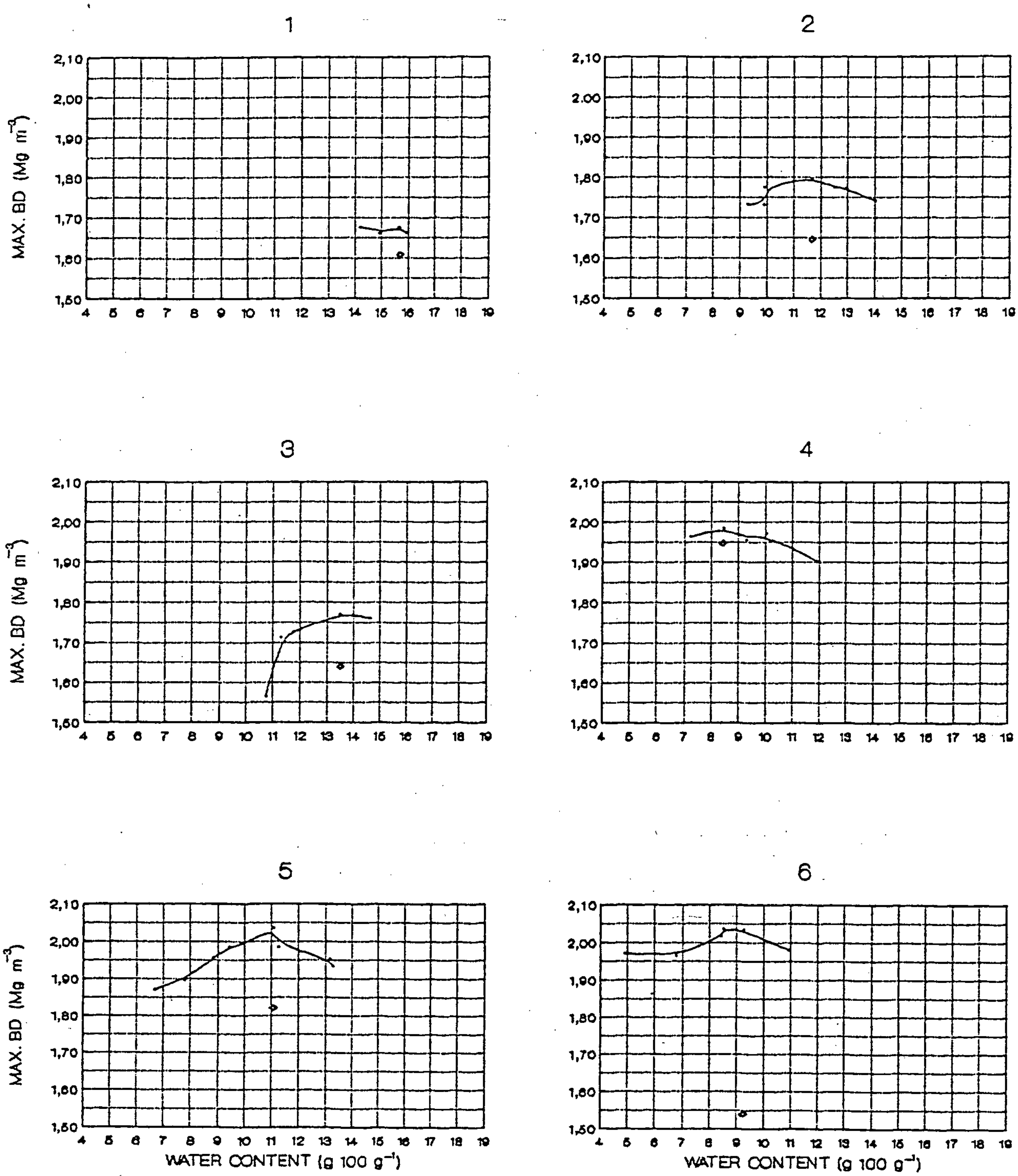


Fig. A.2. Plots of dry bulk density (BD) *versus* water content determined during Proctor maximum compaction tests on 71 soils differing in mechanical composition. The number above each figure refers to the sample number (◊ = Field measured bulk density).

(continued on next page)

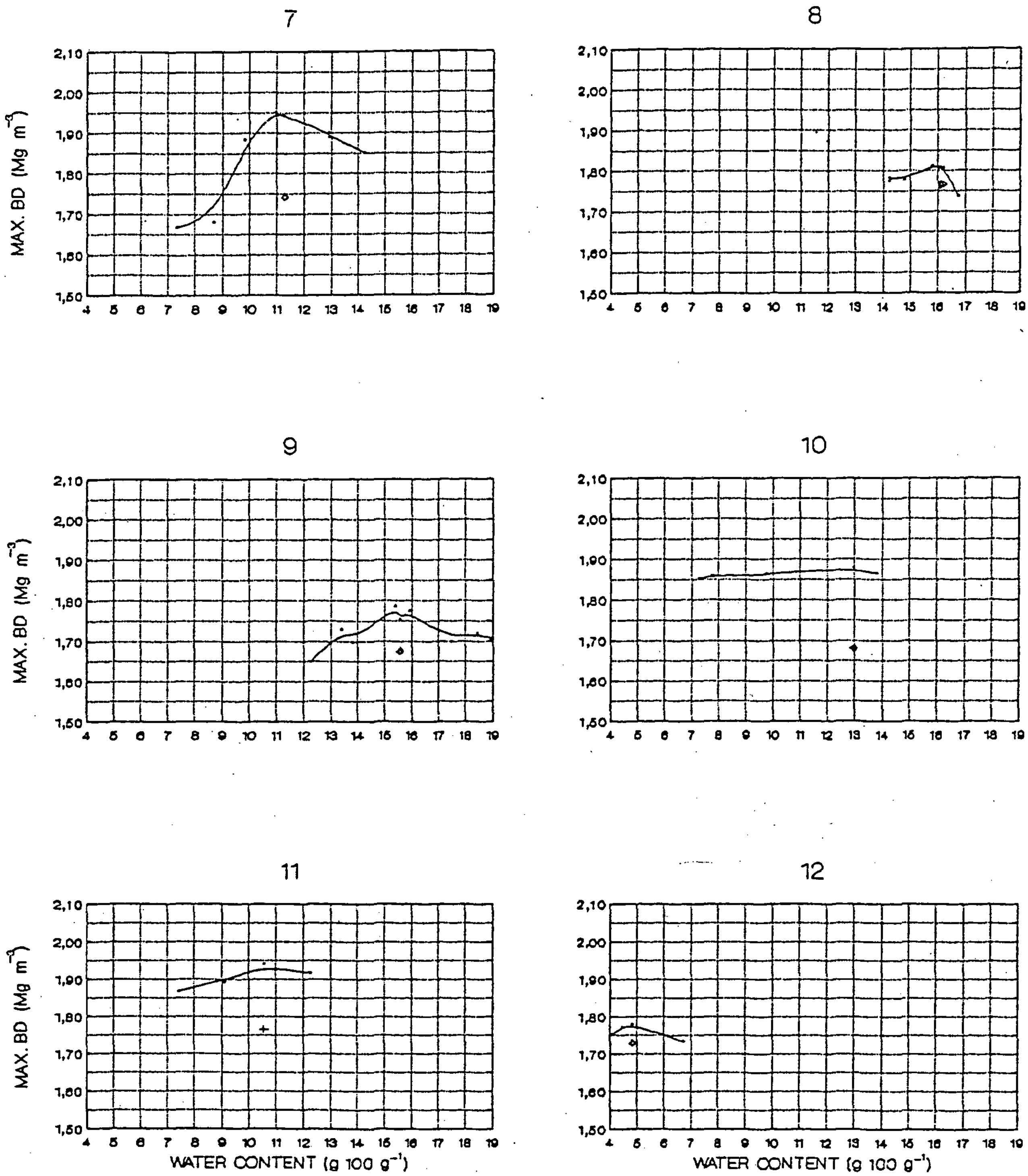


Fig. A.2. Continued.

(continued on next page)

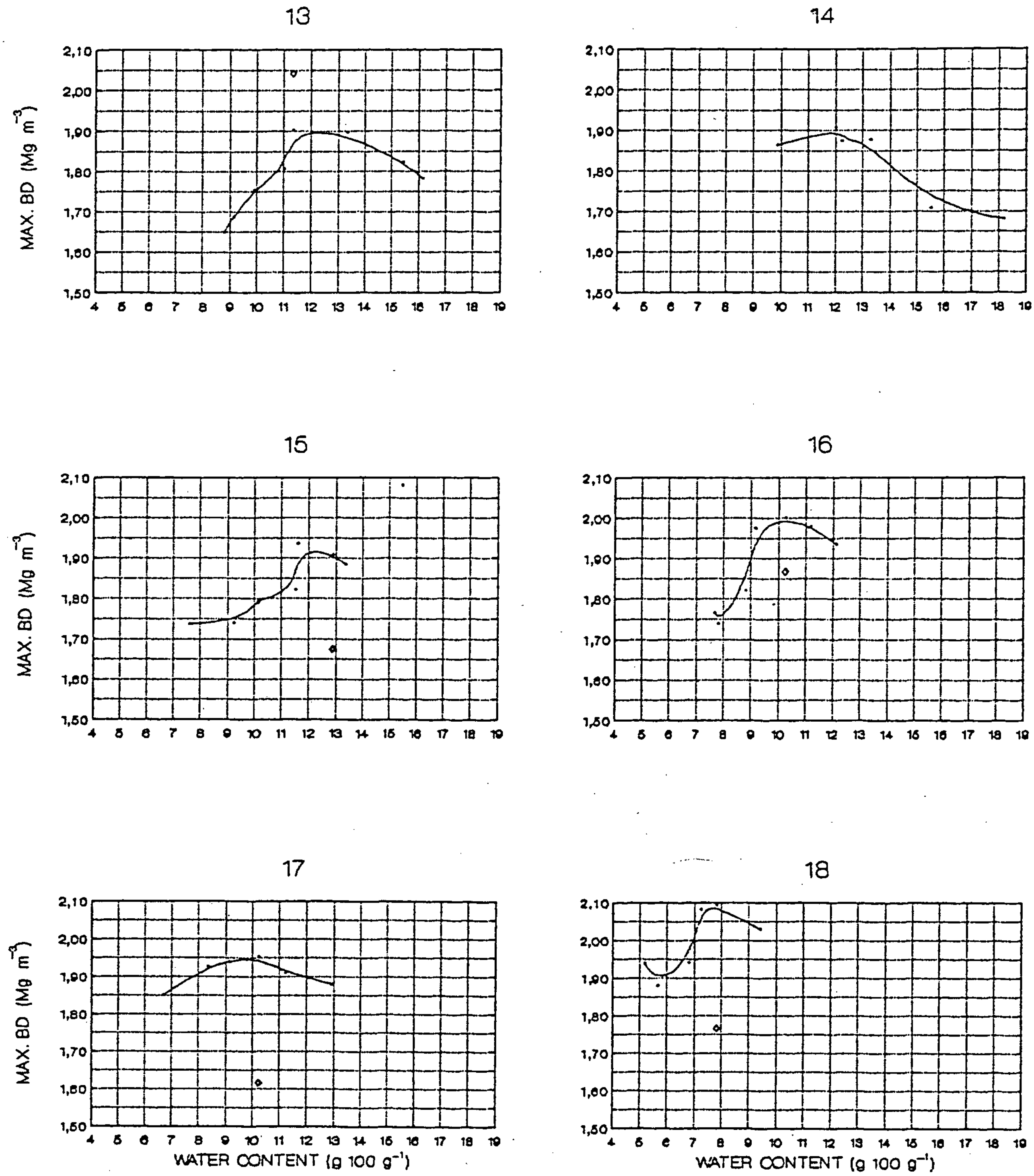


Fig. A.2. Continued.

(continued on next page)

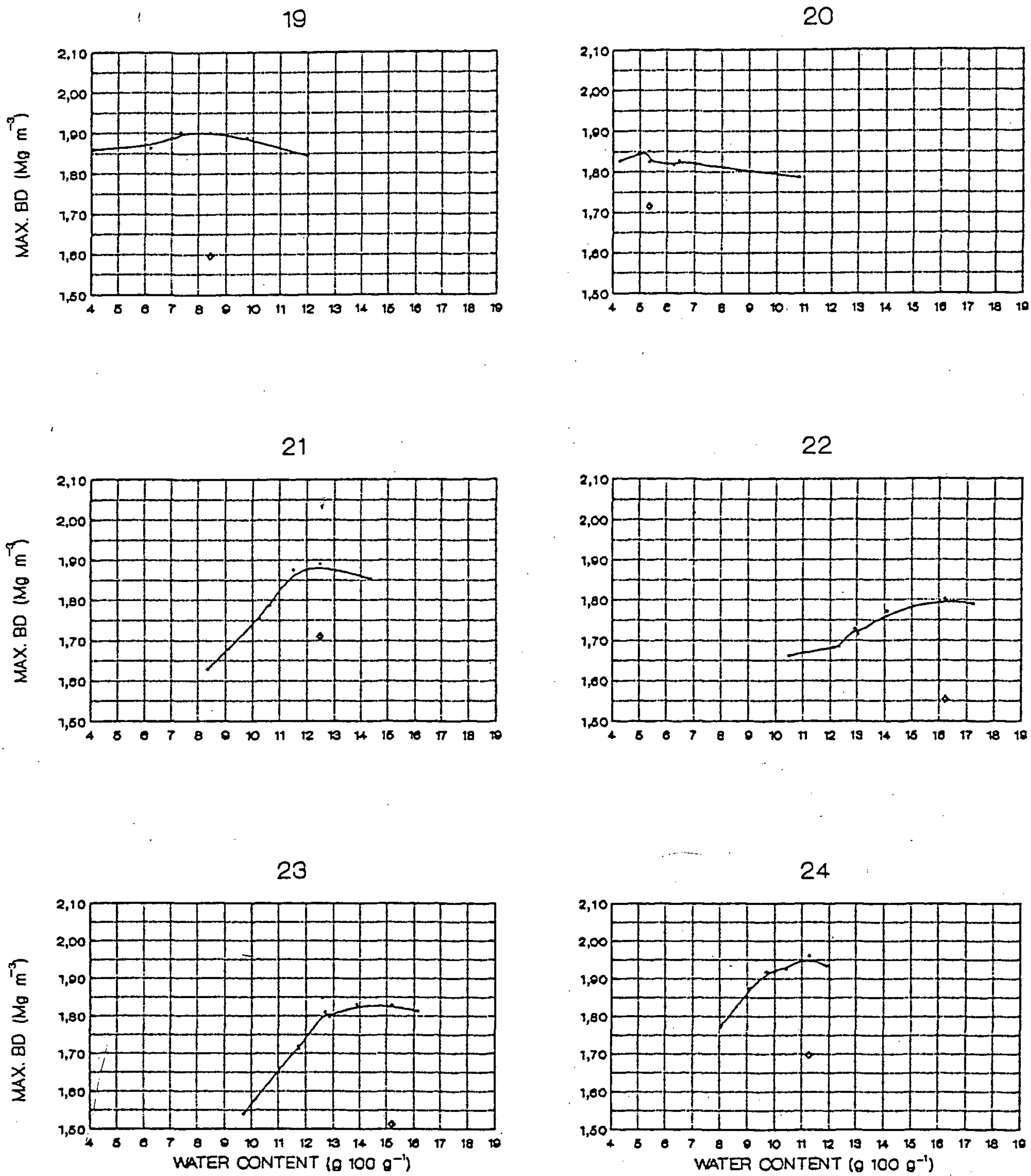


Fig. A.2. Continued.

(continued on next page)

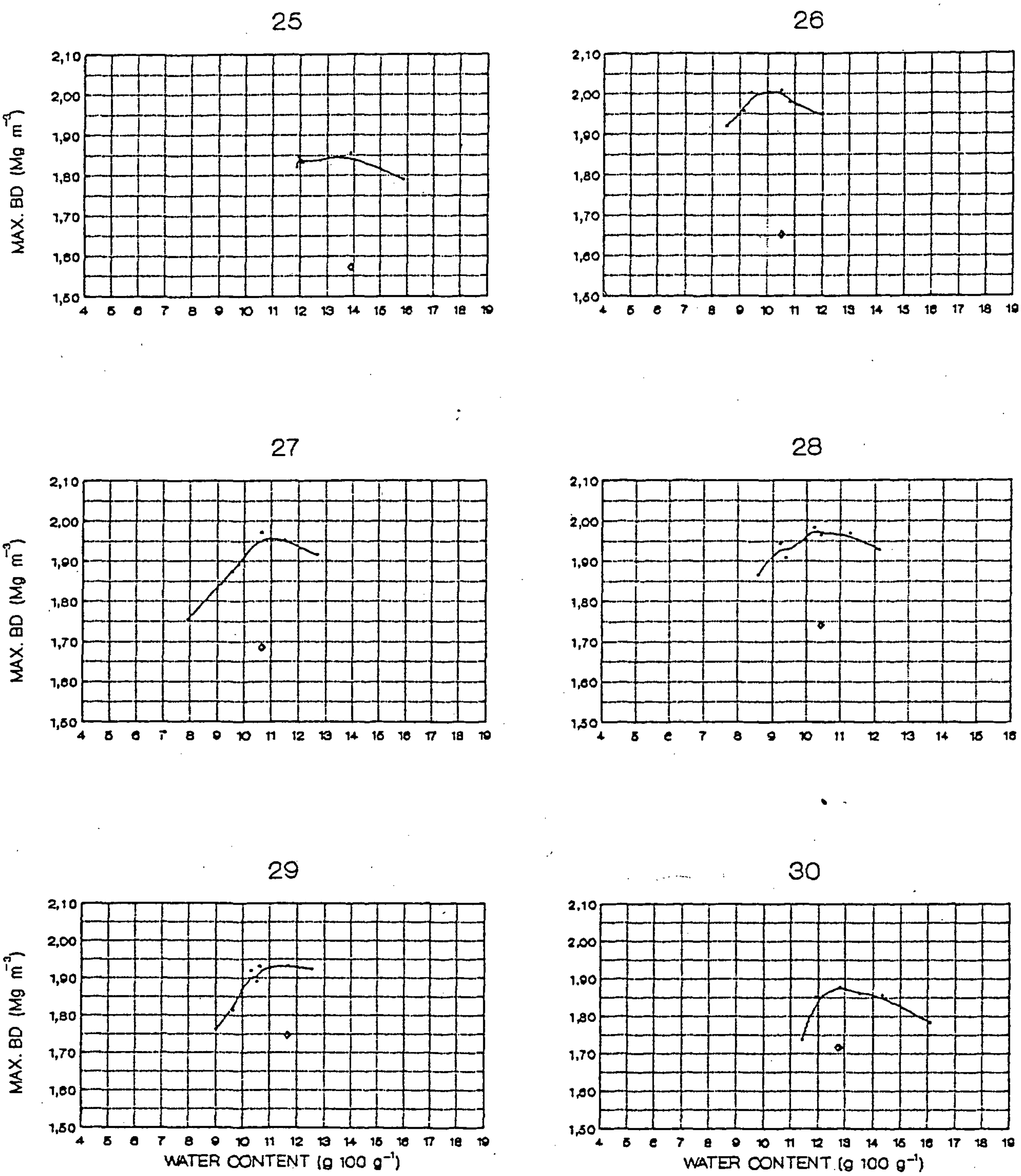


Fig. A.2. Continued.

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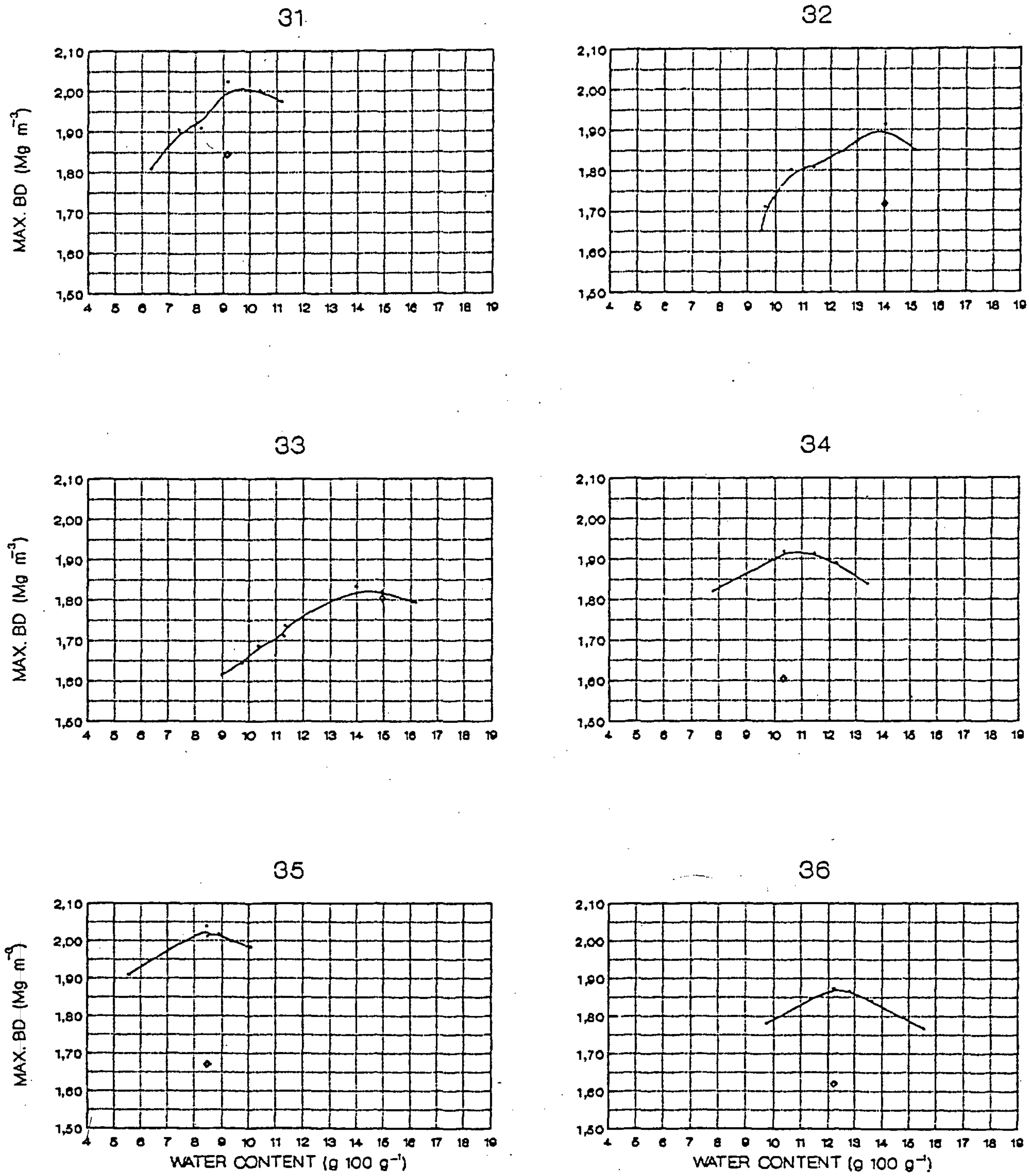


Fig. A.2. Continued.

(continued on next page)

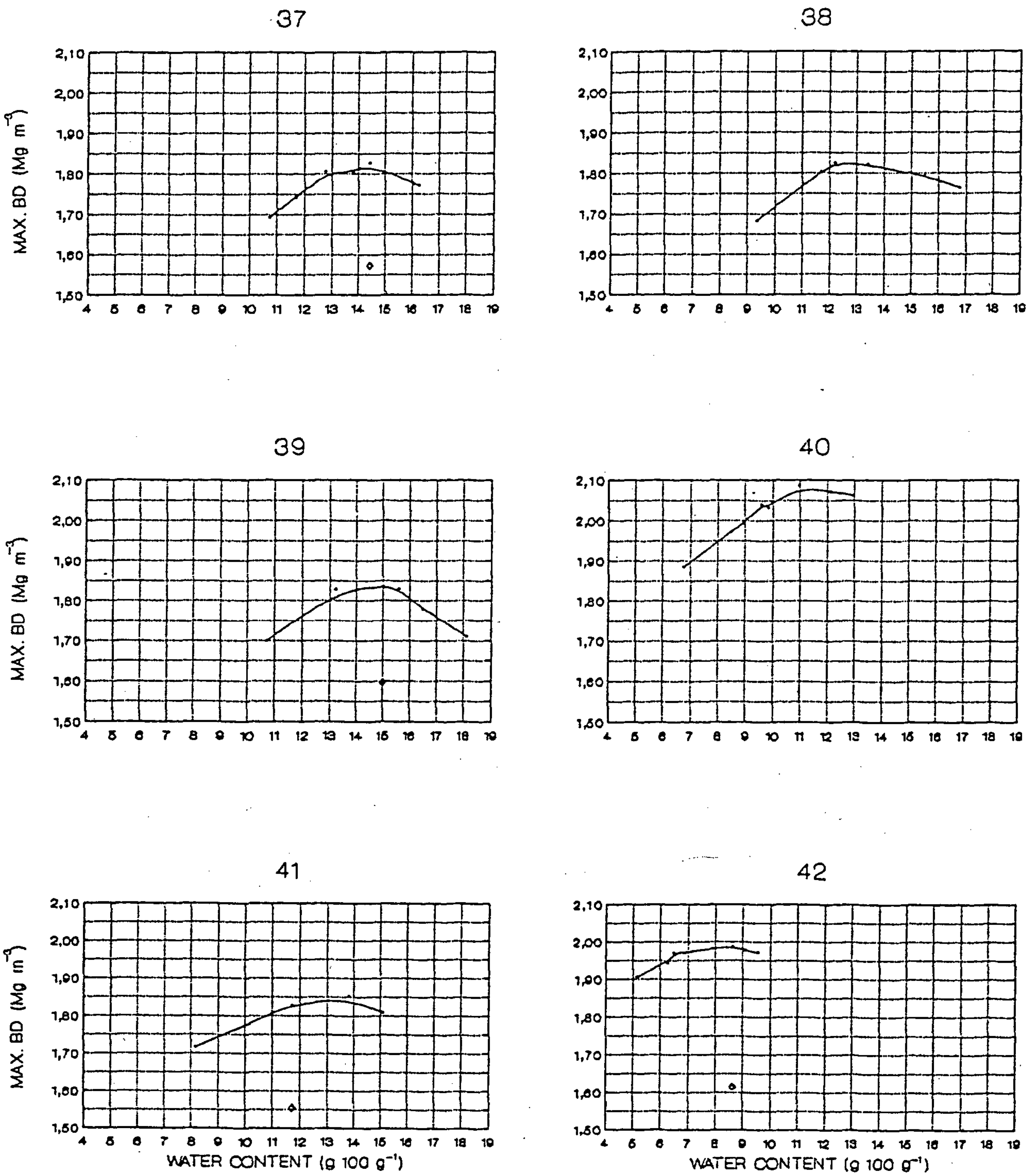


Fig. A.2. Continued.

(continued on next page)

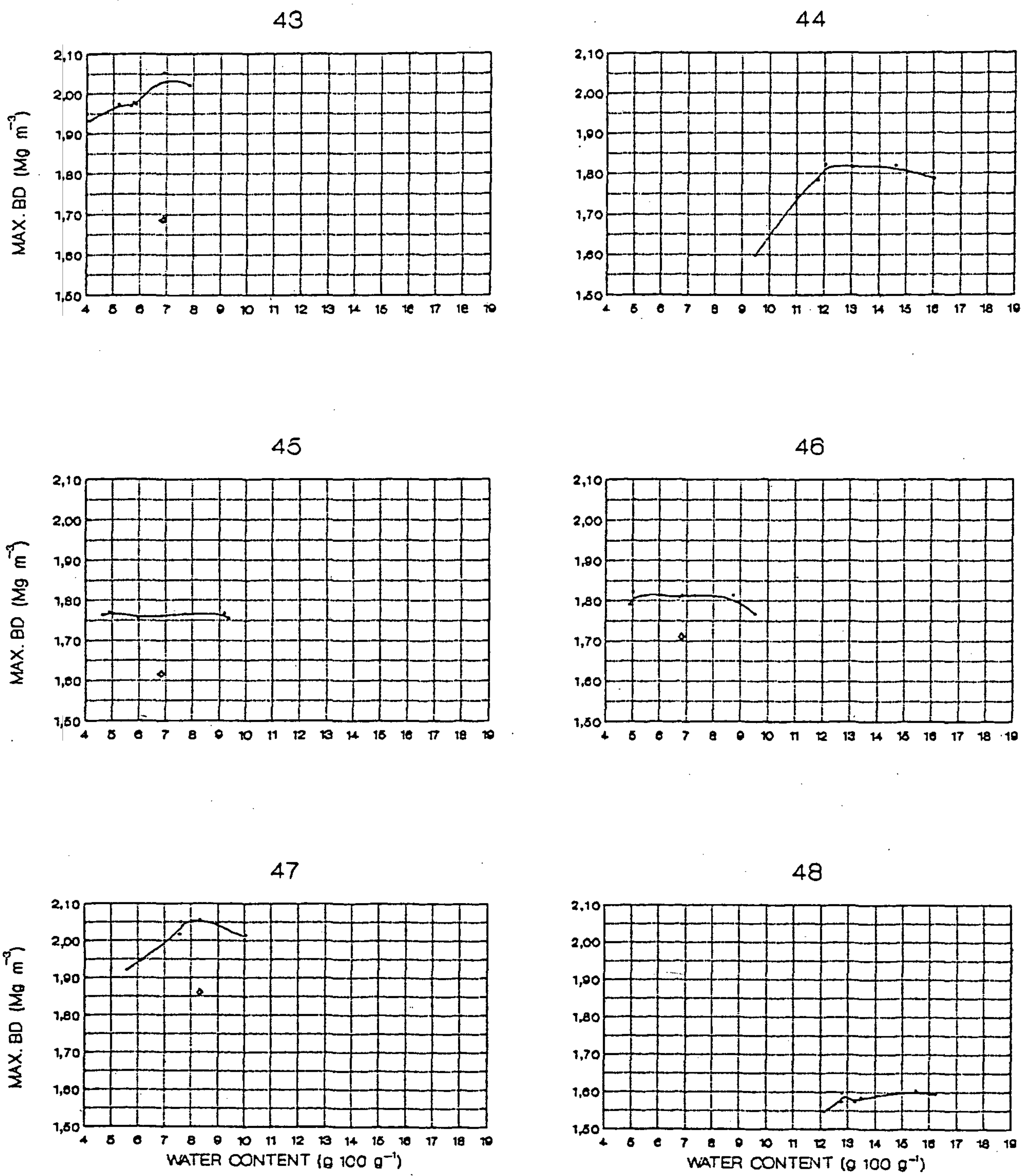


Fig. A.2. Continued.

(continued on next page)

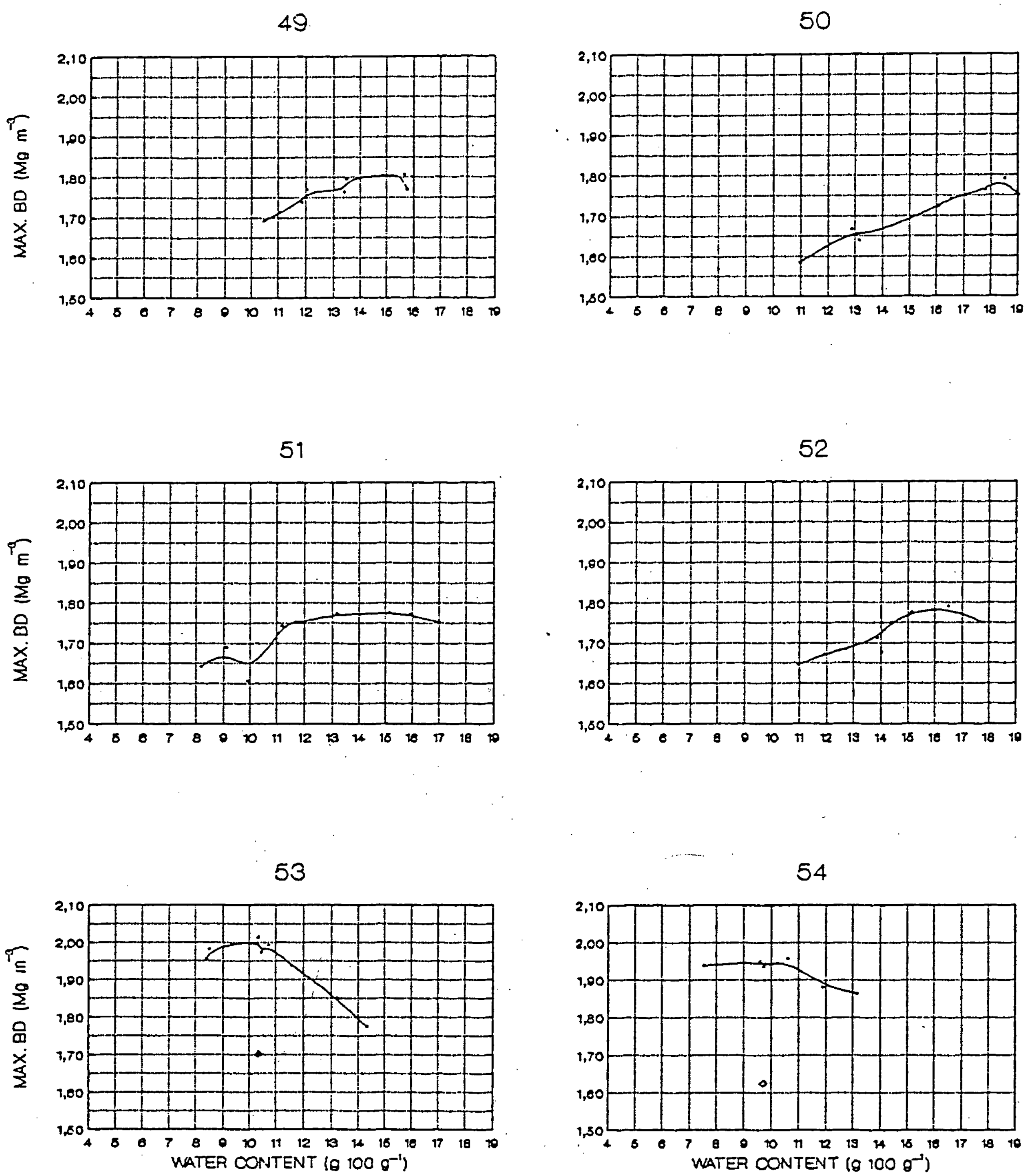


Fig. A.2. Continued.

(continued on next page)

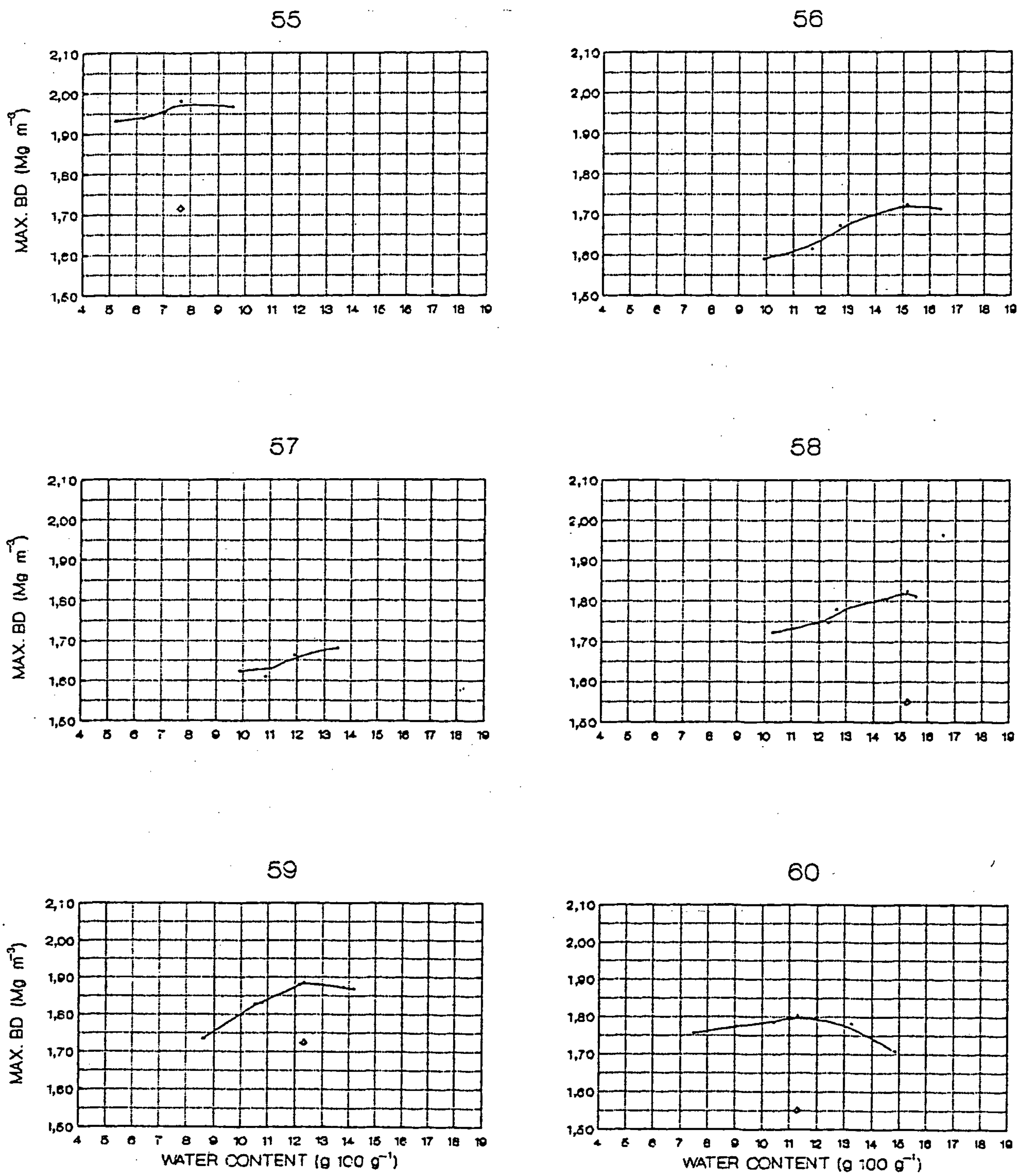


Fig. A.2. Continued.

(continued on next page)

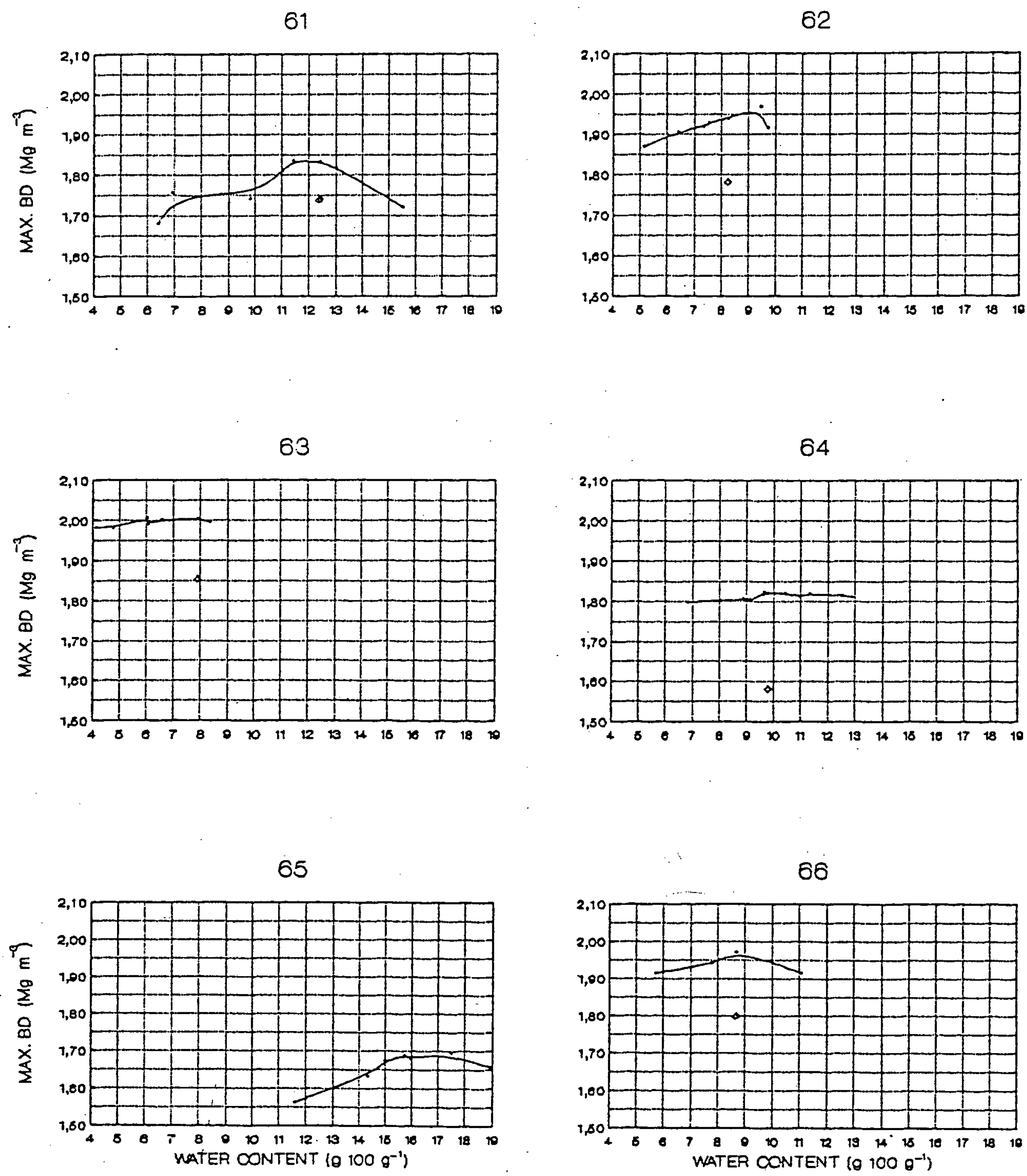


Fig. A.2. Continued.

(continued on next page)

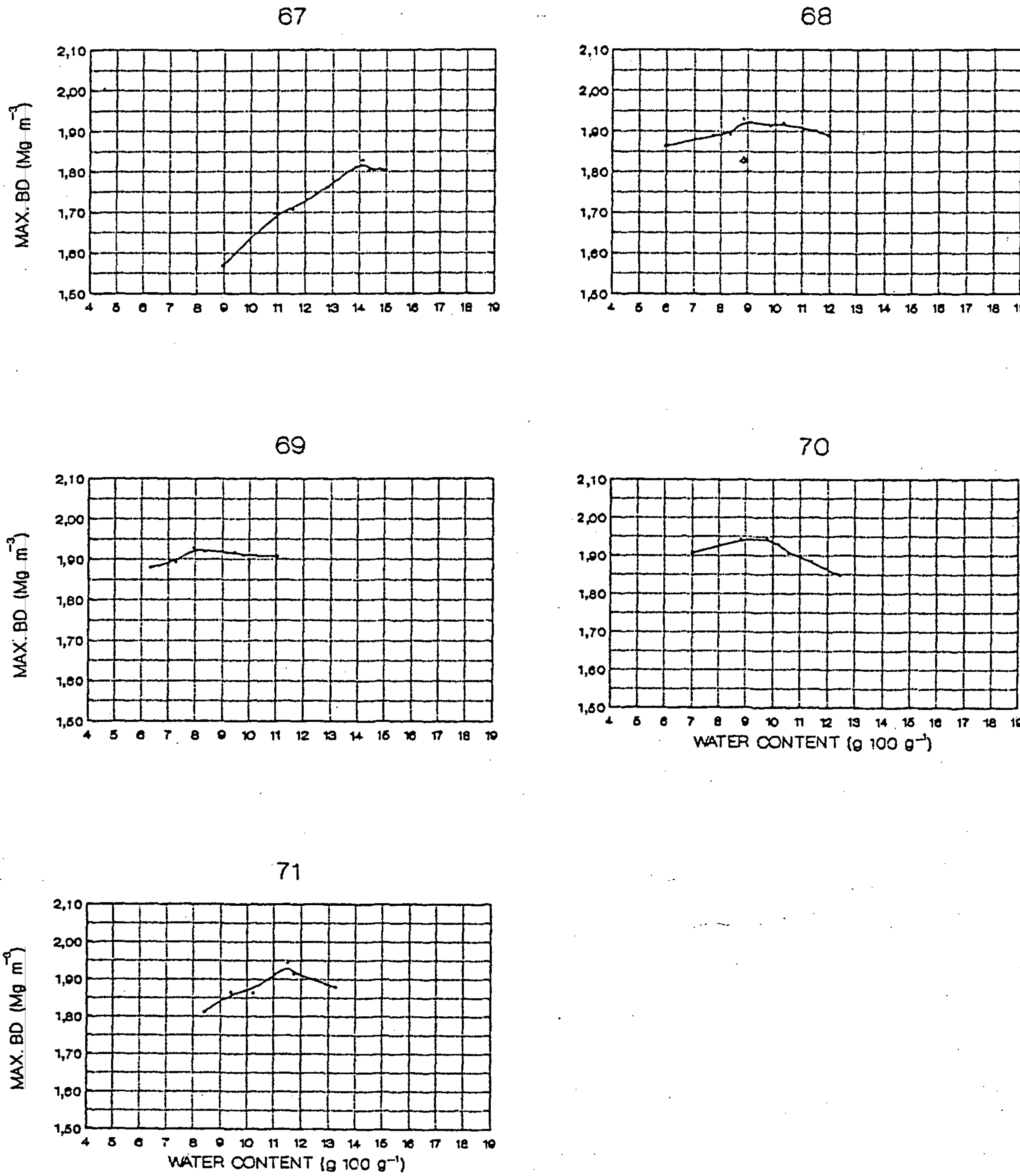


Fig. A.2. Continued.

Appendix 6. Particle density of the different soils and of the different size fractions of each soil included in the compaction study.

| Sample No. | Soil (<2 mm) | Particle density (Mg m$^{-3}$) of different size fractions | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 6,000 to 2,000 mm | 2,000 to 1,000 mm | 1,000 to 0,500 mm | 0,500 to 0,300 mm | 0,300 to 0,250 mm | 0,250 to 0,106 mm | 0,106 to 0,075 mm | 0,075 to 0,050 mm | 0,050 to 0,020 mm | <0,020 mm |
| 1 | 2,664 | - | 2,663 | 2,663 | 2,663 | 2,663 | 2,663 | 2,685 | 2,682 | 2,725 | 2,695 |
| 2 | 2,634 | - | 2,649 | 2,652 | 2,645 | 2,665 | 2,647 | 2,649 | 2,651 | 2,659 | 2,646 |
| 3 | 2,605 | 2,736 | 2,605 | 2,605 | 2,605 | 2,643 | 2,653 | 2,653 | 2,652 | 2,662 | 2,662 |
| 4 | 2,650 | 2,757 | 2,644 | 2,649 | 2,635 | 2,643 | 2,659 | 2,659 | 2,661 | 2,670 | 2,662 |
| 5 | 2,674 | 2,844 | 2,678 | 2,670 | 2,664 | 2,665 | 2,663 | 2,659 | 2,670 | 2,677 | 2,705 |
| 6 | 2,606 | 2,634 | 2,655 | 2,658 | 2,646 | 2,662 | 2,638 | 2,669 | 2,66 | 2,677 | 2,655 |
| 7 | 2,616 | 2,624 | 2,663 | 2,656 | 2,657 | 2,660 | 2,634 | 2,629 | 2,646 | 2,630 | 2,789 |
| 8 | 2,662 | 2,636 | 2,653 | 2,644 | 2,627 | 2,620 | 2,638 | 2,658 | 2,682 | 2,658 | 2,793 |
| 9 | 2,657 | 2,640 | 2,649 | 2,648 | 2,637 | 2,640 | 2,635 | 2,638 | 2,617 | 2,691 | 2,762 |
| 10 | 2,640 | 2,640 | 2,635 | 2,636 | 2,624 | 2,661 | 2,651 | 2,651 | 2,642 | 2,689 | 2,689 |
| 11 | 2,636 | 2,698 | 2,647 | 2,649 | 2,649 | 2,647 | 2,642 | 2,657 | 2,667 | 2,699 | 2,699 |
| 12 | 2,646 | 2,695 | 2,645 | 2,647 | 2,646 | 2,645 | 2,647 | 2,660 | 2,660 | 2,680 | 2,680 |
| 13 | 2,656 | 2,641 | 2,640 | 2,643 | 2,647 | 2,627 | 2,648 | 2,657 | 2,657 | 2,680 | 2,695 |
| 14 | 2,593 | 2,736 | 2,623 | 2,650 | 2,643 | 2,647 | 2,650 | 2,662 | 2,673 | 2,673 | 2,694 |
| 15 | 2,614 | 2,762 | 2,629 | 2,644 | 2,635 | 2,647 | 2,659 | 2,672 | 2,673 | 2,673 | 2,628 |
| 16 | 2,636 | - | 2,640 | 2,644 | 2,633 | 2,638 | 2,643 | 2,637 | 2,633 | 2,633 | 2,683 |
| 17 | 2,580 | 2,642 | 2,632 | 2,630 | 2,630 | 2,632 | 2,640 | 2,645 | 2,620 | 2,664 | 2,608 |
| 18 | 2,609 | 2,650 | 2,634 | 2,634 | 2,630 | 2,633 | 2,636 | 2,650 | 2,656 | 2,696 | 2,649 |
| 19 | 2,643 | - | 2,648 | 2,653 | 2,654 | 2,667 | 2,657 | 2,664 | 2,657 | 2,657 | 2,650 |
| 20 | 2,640 | 2,636 | 2,634 | 2,639 | 2,640 | 2,635 | 2,641 | 2,648 | 2,661 | 2,687 | 2,663 |
| 21 | 2,647 | 2,667 | 2,641 | 2,635 | 2,636 | 2,632 | 2,645 | 2,626 | 2,646 | 2,665 | 2,857 |
| 22 | 2,672 | 2,651 | 2,647 | 2,648 | 2,663 | 2,667 | 2,659 | 2,668 | 2,671 | 2,677 | 2,807 |
| 23 | 2,687 | 2,635 | 2,644 | 2,644 | 2,640 | 2,637 | 2,647 | 2,649 | 2,644 | 2,666 | 2,892 |
| 24 | 2,653 | 2,633 | 2,644 | 2,646 | 2,661 | 2,623 | 2,648 | 2,652 | 2,652 | 2,652 | 2,741 |
| 25 | 2,671 | 2,624 | 2,634 | 2,645 | 2,660 | 2,668 | 2,656 | 2,647 | 2,647 | 2,647 | 2,917 |

(continued on next page)

Appendix 6. Continued.

| Sample No. | Soil (<2 mm) | Particle density (Mg m$^{-3}$) of different size fractions: 6,000 to 2,000 mm | 2,000 to 1,000 mm | 1,000 to 0,500 mm | 0,500 to 0,300 mm | 0,300 to 0,250 mm | 0,250 to 0,106 mm | 0,106 to 0,075 mm | 0,075 to 0,050 mm | 0,050 to 0,020 mm | <0,020 mm |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 26 | 2,673 | 2,634 | 2,639 | 2,636 | 2,636 | 2,621 | 2,645 | 2,641 | 2,641 | 2,641 | 2,900 |
| 27 | 2,671 | 2,635 | 2,640 | 2,645 | 2,640 | 2,655 | 2,631 | 2,641 | 2,641 | 2,641 | 2,788 |
| 28 | 2,648 | 2,648 | 2,637 | 2,643 | 2,633 | 2,633 | 2,637 | 2,644 | 2,63 | 2,629 | 2,799 |
| 29 | 2,674 | 2,662 | 2,650 | 2,651 | 2,669 | 2,65 | 2,631 | 2,610 | 2,603 | 2,603 | 2,629 |
| 30 | 2,677 | 2,658 | 2,645 | 2,644 | 2,668 | 2,623 | 2,645 | 2,660 | 2,615 | 2,615 | 2,819 |
| 31 | 2,648 | 2,635 | 2,642 | 2,643 | 2,628 | 2,641 | 2,646 | 2,646 | 2,628 | 2,643 | 2,804 |
| 32 | 2,655 | 2,671 | 2,647 | 2,650 | 2,645 | 2,657 | 2,668 | 2,653 | 2,654 | 2,654 | 2,710 |
| 33 | 2,663 | 2,666 | 2,652 | 2,657 | 2,674 | 2,650 | 2,625 | 2,611 | 2,609 | 2,606 | 2,744 |
| 34 | 2,622 | 2,655 | 2,637 | 2,648 | 2,641 | 2,632 | 2,646 | 2,650 | 2,649 | 2,649 | 2,649 |
| 35 | 2,639 | 2,622 | 2,632 | 2,641 | 2,642 | 2,644 | 2,646 | 2,646 | 2,642 | 2,642 | 2,642 |
| 36 | 2,633 | 2,650 | 2,635 | 2,631 | 2,643 | 2,637 | 2,641 | 2,661 | 2,669 | 2,669 | 2,902 |
| 37 | 2,662 | 2,650 | 2,662 | 2,662 | 2,661 | 2,687 | 2,664 | 2,655 | 2,658 | 2,668 | 2,822 |
| 38 | 2,764 | 2,653 | 2,666 | 2,666 | 2,656 | 2,669 | 2,653 | 2,692 | 2,666 | 2,666 | 2,864 |
| 39 | 2,682 | 2,768 | 2,668 | 2,654 | 2,653 | 2,664 | 2,658 | 2,668 | 2,668 | 2,668 | 2,778 |
| 40 | 2,691 | 2,872 | 2,686 | 2,681 | 2,681 | 2,672 | 2,671 | 2,664 | 2,664 | 2,664 | 2,798 |
| 41 | 2,674 | - | 2,667 | 2,664 | 2,660 | 2,654 | 2,672 | 2,672 | 2,672 | 2,672 | 2,741 |
| 42 | 2,635 | 2,664 | 2,649 | 2,643 | 2,640 | 2,633 | 2,636 | 2,633 | 2,625 | 2,661 | 2,707 |
| 43 | 2,649 | 2,669 | 2,651 | 2,644 | 2,642 | 2,641 | 2,639 | 2,639 | 2,639 | 2,639 | 2,734 |
| 44 | 2,656 | 2,621 | 2,608 | 2,619 | 2,620 | 2,624 | 2,628 | 2,612 | 2,604 | 2,604 | 2,769 |
| 45 | 2,644 | 2,64 | 2,631 | 2,636 | 2,639 | 2,626 | 2,645 | 2,641 | 2,629 | 2,629 | 2,637 |
| 46 | 2,628 | 2,640 | 2,631 | 2,640 | 2,640 | 2,628 | 2,653 | 2,653 | 2,672 | 2,672 | 2,672 |
| 47 | 2,633 | 2,678 | 2,645 | 2,645 | 2,642 | 2,640 | 2,649 | 2,660 | 2,657 | 2,657 | 2,806 |
| 48 | 2,627 | 2,640 | 2,671 | 2,671 | 2,649 | 2,648 | 2,646 | 2,667 | 2,667 | 2,667 | 2,754 |
| 49 | 2,683 | 2,650 | 2,649 | 2,649 | 2,649 | 2,649 | 2,672 | 2,688 | 2,692 | 2,692 | 2,973 |
| 50 | 2,714 | - | 2,649 | 2,649 | 2,649 | 2,649 | 2,672 | 2,688 | 2,692 | 2,692 | 2,857 |

(continued on next page)

Appendix 6. Continued.

| Sample No. | Particle density ($Mg\ m^{-3}$) of different size fractions | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Soil (<2 mm) | 6,000 to 2,000 mm | 2,000 to 1,000 mm | 1,000 to 0,500 mm | 0,500 to 0,300 mm | 0,300 to 0,250 mm | 0,250 to 0,106 mm | 0,106 to 0,075 mm | 0,075 to 0,050 mm | 0,050 to 0,020 mm | <0,020 mm |
| 51 | 2,686 | - | 2,703 | 2,703 | 2,703 | 2,703 | 2,687 | 2,687 | 2,681 | 2,671 | 2,820 |
| 52 | 2,698 | - | 2,675 | 2,675 | 2,675 | 2,675 | 2,683 | 2,688 | 2,679 | 2,665 | 2,776 |
| 53 | 2,651 | 2,625 | 2,641 | 2,645 | 2,650 | 2,648 | 2,655 | 2,662 | 2,702 | 2,702 | 2,753 |
| 54 | 2,632 | 2,625 | 2,688 | 2,643 | 2,650 | 2,641 | 2,659 | 2,666 | 2,679 | 2,679 | 2,802 |
| 55 | 2,632 | 2,652 | 2,646 | 2,637 | 2,646 | 2,653 | 2,666 | 2,691 | 2,719 | 2,719 | 2,719 |
| 56 | 2,673 | - | 2,673 | 2,673 | 2,673 | 2,673 | 2,686 | 2,690 | 2,705 | 2,705 | 2,851 |
| 57 | 2,687 | - | 2,687 | 2,687 | 2,687 | 2,687 | 2,713 | 2,684 | 2,718 | 2,718 | 2,802 |
| 58 | 2,704 | - | 2,704 | 2,704 | 2,704 | 2,704 | 2,710 | 2,719 | 2,719 | 2,719 | 2,956 |
| 59 | 2,650 | 2,650 | 2,663 | 2,663 | 2,663 | 2,620 | 2,646 | 2,653 | 2,660 | 2,715 | 2,715 |
| 60 | 2,652 | - | 2,651 | 2,651 | 2,651 | 2,633 | 2,644 | 2,650 | 2,658 | 2,701 | 2,860 |
| 61 | 2,657 | 2,657 | 2,655 | 2,655 | 2,655 | 2,649 | 2,647 | 2,651 | 2,690 | 2,701 | 2,807 |
| 62 | 2,631 | 2,670 | 2,638 | 2,639 | 2,642 | 2,642 | 2,647 | 2,623 | 2,650 | 2,677 | 2,677 |
| 63 | 2,645 | 2,645 | 2,643 | 2,645 | 2,650 | 2,656 | 2,657 | 2,636 | 2,618 | 2,618 | 2,618 |
| 64 | 2,679 | 2,679 | 2,635 | 2,635 | 2,645 | 2,654 | 2,658 | 2,671 | 2,683 | 2,625 | 2,832 |
| 65 | 2,613 | 2,613 | 2,613 | 3,613 | 2,613 | 2,632 | 2,649 | 2,648 | 2,646 | 2,668 | 2,775 |
| 66 | 2,651 | 2,651 | 2,660 | 2,644 | 2,646 | 2,634 | 2,646 | 2,662 | 2,639 | 2,600 | 2,836 |
| 67 | 2,606 | 2,597 | 2,606 | 2,637 | 2,643 | 2,642 | 2,644 | 2,658 | 2,643 | 2,616 | 2,777 |
| 68 | 2,625 | 2,635 | 2,535 | 2,653 | 2,642 | 2,648 | 2,648 | 2,649 | 2,649 | 2,649 | 2,649 |
| 69 | 2,653 | 2,630 | 2,640 | 2,648 | 2,650 | 2,650 | 2,655 | 2,650 | 2,649 | 2,711 | 2,711 |
| 70 | 2,619 | 2,908 | 2,638 | 2,638 | 2,638 | 2,642 | 2,646 | 2,646 | 2,651 | 2,711 | 2,722 |
| 71 | 2,665 | 2,781 | 2,667 | 2,667 | 2,690 | 2,661 | 2,659 | 2,646 | 2,655 | 2,687 | 2,773 |
| Mean | 2,650 | 2,669 | 2,648 | 2,649 | 2,649 | 2,648 | 2,652 | 2,656 | 2,657 | 2,666 | 2,753 |

Appendix 7. Maximum bulk density of the different size fractions of each soil included in the compaction study.

| Sample No. | Maximum bulk density ($Mg\ m^{-3}$) of different size fractions | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 6,000 to 2,000 mm | 2,000 to 1,000 mm | 1,000 to 0,500 mm | 0,500 to 0,300 mm | 0,300 to 0,250 mm | 0,250 to 0,106 mm | 0,106 to 0,075 mm | 0,075 to 0,050 mm | 0,050 to 0,020 mm |
| 1 | - | 1,497 | 1,497 | 1,497 | 1,497 | 1,497 | 1,484 | 1,487 | 1,381 |
| 2 | - | 1,542 | 1,542 | 1,514 | 1,516 | 1,522 | 1,445 | 1,424 | 1,215 |
| 3 | 1,433 | 1,458 | 1,458 | 1,458 | 1,463 | 1,468 | 1,428 | 1,401 | 1,323 |
| 4 | 1,475 | 1,502 | 1,502 | 1,502 | 1,502 | 1,539 | 1,500 | 1,485 | 1,438 |
| 5 | 1,583 | 1,464 | 1,403 | 1,458 | 1,494 | 1,481 | 1,501 | 1,514 | 1,423 |
| 6 | 1,457 | 1,541 | 1,518 | 1,409 | 1,317 | 1,413 | 1,337 | 1,373 | 1,346 |
| 7 | 1,431 | 1,455 | 1,486 | 1,438 | 1,328 | 1,444 | 1,346 | 1,368 | 1,263 |
| 8 | 1,399 | 1,447 | 1,421 | 1,285 | 1,162 | 1,258 | 1,044 | 1,680 | 1,230 |
| 9 | 1,392 | 1,385 | 1,196 | 1,111 | 1,053 | 1,076 | 1,035 | 1,035 | 1,080 |
| 10 | 1,473 | 1,517 | 1,559 | 1,493 | 1,585 | 1,556 | 1,517 | 1,354 | 1,182 |
| 11 | 1,457 | 1,484 | 1,523 | 1,554 | 1,498 | 1,568 | 1,515 | 1,434 | 1,414 |
| 12 | 1,481 | 1,544 | 1,542 | 1,491 | 1,485 | 1,556 | 1,435 | 1,278 | 1,300 |
| 13 | 1,449 | 1,533 | 1,519 | 1,549 | 1,415 | 1,536 | 1,453 | 1,307 | 1,307 |
| 14 | 1,464 | 1,463 | 1,463 | 1,429 | 1,336 | 1,489 | 1,475 | 1,446 | 1,331 |
| 15 | 1,418 | 1,348 | 1,348 | 1,375 | 1,349 | 1,489 | 1,460 | 1,485 | 1,485 |
| 16 | 1,418 | 1,326 | 1,326 | 1,404 | 1,347 | 1,492 | 1,436 | 1,473 | 1,473 |
| 17 | 1,481 | 1,457 | 1,458 | 1,377 | 1,304 | 1,428 | 1,426 | 1,329 | 1,274 |
| 18 | 1,446 | 1,444 | 1,430 | 1,404 | 1,376 | 1,413 | 1,363 | 1,376 | 1,300 |
| 19 | - | 1,510 | 1,510 | 1,465 | 1,447 | 1,462 | 1,449 | 1,538 | 1,538 |
| 20 | 1,484 | 1,550 | 1,516 | 1,509 | 1,531 | 1,559 | 1,506 | 1,547 | 1,547 |
| 21 | 1,395 | 1,449 | 1,476 | 1,419 | 1,390 | 1,458 | 1,502 | 1,434 | 1,382 |
| 22 | 1,410 | 1,470 | 1,460 | 1,464 | 1,412 | 1,502 | 1,447 | 1,396 | 1,363 |
| 23 | 1,413 | 1,454 | 1,464 | 1,491 | 1,491 | 1,454 | 1,465 | 1,445 | 1,387 |
| 24 | 1,416 | 1,444 | 1,434 | 1,498 | 1,411 | 1,470 | 1,482 | 1,395 | 1,362 |
| 25 | 1,422 | 1,501 | 1,474 | 1,482 | 1,411 | 1,502 | 1,422 | 1,282 | 1,306 |

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Appendix 7. Continued.

| Sample No. | Maximum bulk density (Mg $m^{-3}$) of different size fractions | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 6,000 to 2,000 mm | 2,000 to 1,000 mm | 1,000 to 0,500 mm | 0,500 to 0,300 mm | 0,300 to 0,250 mm | 0,250 to 0,106 mm | 0,106 to 0,075 mm | 0,075 to 0,050 mm | 0,050 to 0,020 mm |
| 26 | 1,443 | 1,468 | 1,475 | 1,464 | 1,427 | 1,466 | 1,478 | 1,386 | 1,358 |
| 27 | 1,440 | 1,445 | 1,481 | 1,515 | 1,469 | 1,490 | 1,335 | 1,361 | 1,345 |
| 28 | 1,411 | 1,474 | 1,493 | 1,529 | 1,479 | 1,474 | 1,429 | 1,425 | 1,337 |
| 29 | 1,420 | 1,506 | 1,537 | 1,514 | 1,478 | 1,488 | 1,396 | 1,389 | 1,336 |
| 30 | 1,384 | 1,487 | 1,464 | 1,446 | 1,430 | 1,445 | 1,430 | 1,425 | 1,283 |
| 31 | 1,422 | 1,470 | 1,477 | 1,468 | 1,433 | 1,480 | 1,419 | 1,374 | 1,353 |
| 32 | 1,407 | 1,429 | 1,462 | 1,470 | 1,429 | 1,448 | 1,347 | 1,325 | 1,300 |
| 33 | 1,414 | 1,436 | 1,441 | 1,465 | 1,349 | 1,368 | 1,253 | 1,179 | 1,172 |
| 34 | 1,404 | 1,443 | 1,430 | 1,438 | 1,439 | 1,511 | 1,501 | 1,510 | 1,302 |
| 35 | 1,403 | 1,400 | 1,454 | 1,471 | 1,454 | 1,520 | 1,463 | 1,471 | 1,408 |
| 36 | 1,407 | 1,402 | 1,403 | 1,439 | 1,451 | 1,495 | 1,507 | 1,537 | 1,423 |
| 37 | 1,371 | 1,431 | 1,441 | 1,442 | 1,502 | 1,499 | 1,443 | 1,392 | 1,409 |
| 38 | 1,352 | 1,357 | 1,418 | 1,468 | 1,417 | 1,506 | 1,512 | 1,445 | 1,413 |
| 39 | 1,366 | 1,464 | 1,458 | 1,493 | 1,417 | 1,448 | 1,492 | 1,426 | 1,500 |
| 40 | 1,593 | 1,473 | 1,311 | 1,369 | 1,375 | 1,469 | 1,453 | 1,327 | 1,133 |
| 41 | – | 1,411 | 1,411 | 1,451 | 1,410 | 1,482 | 1,400 | 1,378 | 1,200 |
| 42 | 1,467 | 1,490 | 1,474 | 1,509 | 1,436 | 1,463 | 1,443 | 1,468 | 1,247 |
| 43 | 1,457 | 1,460 | 1,453 | 1,462 | 1,478 | 1,493 | 1,494 | 1,437 | 1,250 |
| 44 | 1,366 | 1,440 | 1,465 | 1,492 | 1,511 | 1,510 | 1,439 | 1,418 | 1,246 |
| 45 | 1,462 | 1,425 | 1,518 | 1,493 | 1.495 | 1,461 | 1,446 | 1,412 | 1,191 |
| 46 | 1,519 | 1,480 | 1,549 | 1,438 | 1,440 | 1,460 | 1,500 | 1,392 | 1,361 |
| 47 | 1,357 | 1,439 | 1,466 | 1,504 | 1,549 | 1,541 | 1,485 | 1,433 | 1,247 |
| 48 | 1,306 | 1,304 | 1,339 | 1,432 | 1,413 | 1,373 | 1,300 | 1,276 | 1,150 |
| 49 | 1,432 | 1,446 | 1,446 | 1,446 | 1,446 | 1,430 | 1,517 | 1,449 | 1,313 |
| 50 | – | 1,427 | 1,427 | 1,427 | 1,427 | 1,482 | 1,423 | 1,409 | 1,182 |

(continued on next page)

Appendix 7. Continued.

| Sample No. | Maximum bulk density (Mg $m^{-3}$) of different size fractions | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 6,000 to 2,000 mm | 2,000 to 1,000 mm | 1,000 to 0,500 mm | 0,500 to 0,300 mm | 0,300 to 0,250 mm | 0,250 to 0,106 mm | 0,106 to 0,075 mm | 0,075 to 0,050 mm | 0,050 to 0,020 mm |
| 51 | - | 1,596 | 1,596 | 1,596 | 1,596 | 1,474 | 1,463 | 1,368 | 1,344 |
| 52 | - | 1,517 | 1,517 | 1,517 | 1,517 | 1,459 | 1,513 | 1,407 | 1,242 |
| 53 | 1,416 | 1,434 | 1,449 | 1,487 | 1,496 | 1,566 | 1,518 | 1,460 | 1,236 |
| 54 | 1,398 | 1,445 | 1,493 | 1,438 | 1,511 | 1,542 | 1,516 | 1,518 | 1,405 |
| 55 | 1,424 | 1,494 | 1,513 | 1,432 | 1,502 | 1,558 | 1,537 | 1,503 | 1,375 |
| 56 | - | 1,427 | 1,427 | 1,427 | 1,427 | 1,427 | 1,431 | 1,464 | 1,494 |
| 57 | - | 1,471 | 1,471 | 1,471 | 1,471 | 1,471 | 1,423 | 1,443 | 1,398 |
| 58 | - | 1,433 | 1,433 | 1,433 | 1,433 | 1,433 | 1,478 | 1,418 | 1,457 |
| 59 | 1,432 | 1,431 | 1,435 | 1,435 | 1,462 | 1,469 | 1,460 | 1,449 | 1,358 |
| 60 | - | 1,428 | 1,420 | 1,412 | 1,422 | 1,461 | 1,479 | 1,489 | 1,459 |
| 61 | 1,432 | 1,419 | 1,419 | 1,417 | 1,441 | 1,465 | 1,529 | 1,468 | 1,430 |
| 62 | 1,432 | 1,418 | 1,442 | 1,424 | 1,451 | 1,440 | 1,422 | 1,443 | 1,363 |
| 63 | 1,432 | 1,432 | 1,493 | 1,445 | 1,496 | 1,490 | 1,458 | 1,459 | 1,353 |
| 64 | 1,454 | 1,476 | 1,476 | 1,474 | 1,420 | 1,397 | 1,357 | 1,387 | 1,343 |
| 65 | 1,432 | 1,325 | 1,325 | 1,325 | 1,302 | 1,437 | 1,474 | 1,380 | 1,349 |
| 66 | 1,457 | 1,422 | 1,446 | 1,456 | 1,484 | 1,527 | 1,430 | 1,456 | 1,376 |
| 67 | 1,437 | 1,470 | 1,505 | 1,502 | 1,477 | 1,489 | 1,460 | 1,421 | 1,338 |
| 68 | 1,432 | 1,507 | 1,499 | 1,414 | 1,408 | 1,448 | 1,482 | 1,368 | 1,349 |
| 69 | 1,432 | 1,476 | 1,452 | 1,460 | 1,467 | 1,518 | 1,443 | 1,434 | 1,350 |
| 70 | 1,388 | 1,431 | 1,447 | 1,474 | 1,447 | 1,428 | 1,439 | 1,446 | 1,341 |
| 71 | 1,570 | 1,435 | 1,421 | 1,416 | 1,343 | 1,428 | 1,501 | 1,447 | 1,388 |
| Mean | 1,433 | 1,455 | 1,458 | 1,453 | 1,433 | 1,470 | 1,440 | 1,416 | 1,336 |

Appendix 8. Summary statistics of the soil chemical and physical properties of 71 soil samples representing 50 profiles included in a compaction study.

| Variable* | Sample size | Minimum | Maximum | Mean | Median | Lower quartile | Upper quartile | Comment |
|---|---|---|---|---|---|---|---|---|
| (a) <u>Chemical analyses data (for units compare Table 4.2)</u>. | | | | | | | | |
| pH | 71 | 3,860 | 7,850 | 5,054 | 4,650 | 4,310 | 5,570 | |
| Res | 71 | 166 | 8714 | 2505 | 2254 | 1076 | 3436 | |
| P | 71 | 0 | 296,300 | 53,848 | 28,100 | 3,400 | 66,400 | Citric acid |
| K | | 5,100 | 608 | 88,435 | 65,400 | 36,400 | 90,200 | extraction |
| Ex $Ca^{+2}$ | | 0 | 9,768 | 1,755 | 1,019 | 0,519 | 2,047 | |
| Ex $Mg^{+2}$ | | 0 | 4,093 | 1,333 | 0,947 | 0,581 | 1,572 | |
| Ex $Na^{+}$ | | 0 | 1,163 | 0,125 | 0,061 | 0,029 | 0,135 | |
| Ex $K^{+}$ | | 0 | 1,223 | 0,196 | 0,129 | 1,160 | 2,360 | |
| Ex $H^{+}$ | | 0 | 2,450 | 0,707 | 0,580 | 0,170 | 1,060 | |
| Ex $Al^{+3}$ | | 0 | 1,570 | 0,223 | 0,090 | 0 | 0,270 | |
| CEC | | 0,170 | 9,816 | 2,830 | 2,180 | 1,330 | 3,480 | |
| ECEC | | 5,610 | 91,570 | 20,480 | 13,993 | 9,444 | 24,966 | |
| TAl | | 1,090 | 15,005 | 3,633 | 3,633 | 1,781 | 4,402 | |
| TH | | 0,209 | 15,005 | 4,117 | 4,117 | 2,446 | 4,705 | |
| OM | | 0,070 | 3,632 | 0,801 | 0,687 | 0,357 | 1,146 | |
| LR | | 0 | 7,130 | 1,873 | 1,480 | 0 | 3,030 | |

*Variable names as explained on pp. 4.5 to 4.10 in text.

(continued on next page)

Appendix 8. Continued.

| Variable | Sample size | Minimum | Maximum | Mean | Median | Lower quartile | Upper quartile | Comment |
|---|---|---|---|---|---|---|---|---|
| (b) Physical analyses data (for units compare Table 4.3). | | | | | | | | |
| WC | | 4,320 | 18,500 | 11,545 | 11,500 | 9,000 | 14,000 | Proctor |
| MBD | | 1,600 | 2,080 | 1,882 | 1,881 | 1,813 | 1,958 | compaction |
| FBD | | 1,269 | 2,042 | 1,657 | 1,676 | 1,573 | 1,743 | |
| MOR1 | | 0 | 147,633 | 21,678 | 10,428 | 4,436 | 17,314 | 1 Hour |
| MOR2 | | 4,270 | 463,884 | 137,239 | 100,848 | 58,465 | 218,583 | 12 Hours |
| ASP | | 42,500 | 99,020 | 84,720 | 86,760 | 78,370 | 95,140 | |
| A PERM | | 45,976 | 2961,310 | 905,433 | 760,161 | 398,809 | 1244,800 | |
| W PERM | | 3,923 | 139,486 | 31,879 | 24,970 | 5,499 | 44,182 | |
| AWR | 70* | 8,319 | 3512,584 | 117,493 | 37,833 | 21,723 | 69,322 | |
| HC | | 3,835 | 136,362 | 31,165 | 24,411 | 5,375 | 43,192 | |
| TP(1) | 71 | 20,276 | 39,089 | 28,956 | 28,870 | 25,564 | 32,064 | at MBD |
| TP(2) | 68 | 23,126 | 52,548 | 37,451 | 36,796 | 34,342 | 40,951 | at FBD |
| RC | 68 | 69,534 | 107,757 | 88,027 | 87,121 | 83,859 | 91,778 | in field |
| (c) Waterstable aggregates (WSA) per size fraction (%). | | | | | | | | |
| >2 mm | | 0 | 26,691 | 3,847 | 2,183 | 0,136 | 5,409 | |
| 2-1 mm | | 0 | 10,431 | 3,235 | 2,549 | 0,801 | 4,614 | |
| 1-0,5 mm | | 0 | 12,470 | 4,108 | 3,225 | 1,620 | 6,073 | |
| 0,5-0,25 mm | | 0 | 17,203 | 6,076 | 5,187 | 2,720 | 8,885 | |
| 0,25-0,1 mm | | 0 | 22,409 | 7,065 | 6,829 | 2,783 | 11,181 | |
| <0,1 mm | | 50,428 | 96,151 | 75,627 | 77,239 | 66,932 | 85,625 | |
| MWD (mm) | | 0,189 | 2,839 | 0,761 | 0,646 | 0,506 | 0,912 | |
| GMD (mm) | | 0,339 | 1,219 | 0,603 | 0,592 | 0,511 | 0,684 | |

*Sample no. 13 rejected as an outlier.

(continued on next page)

Appendix 8. Continued.

| Variable | Sample size | Minimum | Maximum | Mean | Median | Lower quartile | Upper quartile | Comment |
|---|---|---|---|---|---|---|---|---|
| d) <u>Particle size data (%) on basis <2 mm diameter</u>. | | | | | | | | |
| 2-1 mm | 71 | 0,040 | 29,180 | 6,984 | 4,890 | 0,990 | 11,390 | coarse |
| 1-0,5 mm | 71 | 0,130 | 53,950 | 10,769 | 8,250 | 2,720 | 14,990 | sand |
| 0,5-0,3 mm | 71 | 0,360 | 28,370 | 9,445 | 8,170 | 4,520 | 13,110 | medium |
| 0,3-0,25 mm | 71 | 0,020 | 13,220 | 3,993 | 3,340 | 2,270 | 5,430 | sand |
| 0,25-0,106 mm | 71 | 5,020 | 58,310 | 19,390 | 19,080 | 13,750 | 24,060 | fine sand |
| 0,106-0,075 mm | 71 | 2,020 | 31,190 | 8,781 | 6,960 | 5,090 | 8,820 | very |
| 0,075-0,050 mm | 71 | 1,150 | 20,470 | 4,563 | 4,100 | 3,060 | 5,240 | fine sand |
| 0,050-0,020 mm | 71 | 0,400 | 29,930 | 9,211 | 8,270 | 5,380 | 11,090 | coarse silt |
| 0,020-0,002 mm | 71 | 0,960 | 29,350 | 9,630 | 7,160 | 4,970 | 13,170 | fine silt |
| <0,002 | 71 | 1,170 | 37,630 | 17,711 | 16,290 | 7,710 | 29,290 | clay |
| 2-0,5 | 71 | 0,190 | 69,480 | 17,753 | 13,970 | 5,150 | 24,990 | coarse sand |
| 0,5-0,25 | 71 | 0,650 | 37,360 | 13,438 | 11,020 | 7,330 | 18,870 | medium sand |
| 0,106-0,053 | 71 | 3,700 | 44,480 | 13,344 | 10,850 | 8,250 | 13,530 | very fine sand |
| 0,25-0,053 | 71 | 8,970 | 82,900 | 32,734 | 30,490 | 24,630 | 37,340 | total fine sand |
| 2-0,053 | 71 | 33,960 | 95,400 | 63,925 | 58,700 | 51,000 | 80,490 | total sand |
| 0,053-0,002 | 71 | 2,250 | 46,650 | 18,841 | 15,770 | 11,770 | 26,220 | silt |
| <0,053 | 71 | 4,840 | 67,130 | 36,552 | 40,820 | 20,390 | 49,260 | silt + clay |
| <0,020 | 71 | 2,430 | 50,890 | 27,341 | 29,84 | 12,590 | 39,330 | fine silt + clay |
| ARME | 71 | 0,061 | 0,777 | 0,284 | 0,270 | 0,158 | 0,376 | |
| GME | 71 | 0,160 | 0,507 | 0,098 | 0,048 | 0,031 | 0,115 | |
| GDEV | 71 | 3,260 | 19,595 | 8,874 | 7,111 | 5,386 | 12,537 | |
| SKW | 71 | -0,092 | 2,769 | 1,011 | 0,735 | 0,381 | 1,581 | |
| KUR | 71 | 1,342 | 12,093 | 3,790 | 2,322 | 1,575 | 4,919 | |

(continued on next page)

Appendix 8. Continued.

| Variable | Sample size | Minimum | Maximum | Mean | Median | Lower quartile | Upper quartile | Comment |
|---|---|---|---|---|---|---|---|---|
| (e) Particle size data (%) on basis <6 mm diameter. | | | | | | | | |
| 6-2 mm | 71 | 0 | 61,950 | 7,203 | 2,490 | 0,780 | 8,400 | gravel |
| 2-1 mm | 71 | 0,040 | 26,729 | 6,197 | 4,816 | 0,990 | 9,425 | coarse |
| 1-0,5 mm | 71 | 0,130 | 53,308 | 10,040 | 6,998 | 2,367 | 14,274 | sand |
| 0,5-0,3 mm | 71 | 0,360 | 28,370 | 8,861 | 6,788 | 4,031 | 12,912 | medium |
| 0,3-0,25 mm | 71 | 0,019 | 13,200 | 3,758 | 2,986 | 1,951 | 5,149 | sand |
| 0,25-0,106 mm | 71 | 4,963 | 58,310 | 18,324 | 18,093 | 10,951 | 23,392 | fine sand |
| 0,106-0,075 mm | 71 | 1,970 | 31,190 | 8,317 | 6,597 | 4,353 | 8,440 | very |
| 0,075-0,050 mm | 71 | 0,643 | 20,470 | 4,301 | 3,664 | 2,590 | 4,911 | fine sand |
| 0,050-0,020 mm | 71 | 0,378 | 29,930 | 8,554 | 7,906 | 4,41 | 10,400 | coarse silt |
| 0,020-0,002 mm | 71 | 0,931 | 29,306 | 8,919 | 6,845 | 4,157 | 11,586 | fine silt |
| <0,002 mm | 71 | 1,099 | 34,670 | 15,990 | 14,687 | 7,079 | 24,205 | clay |
| 2-0,5 mm | 71 | 0,190 | 67,750 | 16,237 | 13,682 | 3,639 | 22,211 | coarse sand |
| 0,5-0,25 mm | 71 | 0,650 | 37,360 | 12,619 | 9,257 | 6,364 | 17,740 | medium sand |
| 0,106-0,053 mm | 71 | 3,453 | 44,480 | 12,617 | 9,937 | 6,985 | 13,300 | very fine sand |
| 0,25-0,053 mm | 71 | 8,747 | 82,900 | 30,941 | 29,115 | 20,400 | 36,082 | total fine sand |
| 2-0,053 mm | 71 | 18,032 | 92,327 | 59,797 | 55,230 | 44,729 | 77,560 | total sand |
| 0,053-0,002 mm | 71 | 2,183 | 45,806 | 17,473 | 15,183 | 8,489 | 24,761 | silt |
| <0,053 mm | 71 | 4,553 | 66,029 | 33,463 | 35,800 | 19,451 | 45,407 | silt + clay |
| <0,020 mm | 71 | 2,341 | 50,040 | 24,909 | 25,700 | 12,571 | 36,140 | fine silt + clay |
| ARME | 71 | 0,061 | 2,543 | 0,549 | 0,459 | 0,191 | 0,773 | |
| GME | 71 | 0,163 | 0,604 | 0,133 | 0,079 | 0,039 | 0,180 | |
| GDEV | 71 | 3,302 | 26,811 | 10,480 | 8,340 | 5,563 | 13,849 | |
| SKH | 71 | 0,026 | 2,698 | 0,995 | 0,838 | 0,388 | 1,500 | |
| KUR | 71 | 1,442 | 10,665 | 3,801 | 2,554 | 1,800 | 4,919 | |

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Appendix 8. Continued.

| Variable | Sample size | Minimum | Maximum | Mean | Median | Lower quartile | Upper quartile | Comment |
|---|---|---|---|---|---|---|---|---|
| (f) Particle density (Mg m$^{-3}$) of different size fractions. | | | | | | | | |
| <2 mm | 71 | 2,579 | 2,714 | 2,650 | 2,650 | 2,633 | 2,672 | soil |
| 6-2 mm | 59 | 2,597 | 2,908 | 2,669 | 2,650 | 2,635 | 2,670 | gravel |
| 2-1 mm | 59 | 2,605 | 2,704 | 2,648 | 2,645 | 2,637 | 2,660 | coarse |
| 1-0,5 mm | 59 | 2,605 | 2,704 | 2,649 | 2,646 | 2,641 | 2,655 | sand |
| 0,5-0,3 mm | 59 | 2,605 | 2,704 | 2,649 | 2,646 | 2,640 | 2,660 | medium |
| 0,3-0,25 mm | 59 | 2,620 | 2,704 | 2,648 | 2,647 | 2,634 | 2,660 | sand |
| 0,25-0,106 mm | 59 | 2,625 | 2,713 | 2,652 | 2,648 | 2,644 | 2,659 | fine sand |
| 0,106-0,075 mm | 59 | 2,610 | 2,719 | 2,656 | 2,653 | 2,646 | 2,666 | very |
| 0,075-0,050 mm | 59 | 2,603 | 2,719 | 2,657 | 2,657 | 2,642 | 2,672 | fine sand |
| 0,050-0,020 mm | 59 | 2,600 | 2,725 | 2,666 | 2,668 | 2,647 | 2,687 | coarse silt |
| <0,020 mm | 59 | 2,608 | 2,973 | 2,753 | 2,753 | 2,680 | 2,807 | fine silt |
| (g) Maximum bulk density (Mg m$^{-3}$) of different size fractions. | | | | | | | | |
| 6-2 mm | 60 | 1,306 | 1,593 | 1,433 | 1,432 | 1,407 | 1,457 | gravel |
| 2-1 mm | 60 | 1,304 | 1,596 | 1,455 | 1,454 | 1,431 | 1,484 | coarse |
| 1-0,5 mm | 60 | 1,196 | 1,596 | 1,458 | 1,462 | 1,430 | 1,497 | sand |
| 0,5-0,3 mm | 60 | 1,111 | 1,596 | 1,453 | 1,460 | 1,429 | 1,493 | medium |
| 0,3-0,25 mm | 60 | 1,053 | 1,596 | 1,433 | 1,440 | 1,411 | 1,485 | sand |
| 0,25-0,106 mm | 60 | 1,076 | 1,568 | 1,470 | 1,474 | 1,448 | 1,502 | fine sand |
| 0,106-0,075 | 60 | 1,035 | 1,537 | 1,440 | 1,453 | 1,428 | 1,494 | very |
| 0,075-0,050 | 60 | 1,035 | 1,680 | 1,416 | 1,425 | 1,378 | 1,460 | fine sand |
| 0,050-0,020 | 60 | 1,080 | 1,547 | 1,336 | 1,346 | 1,274 | 1,398 | fine silt |

Appendix 9. Statistical measures of particle size data.

| | Data on basis <2 mm diameter | | | | | Data on basis <6 mm diameter | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Sample No. | Skewness | Kurtosis | Arithmetic mean ϕ (mm) | Geometric mean ϕ (mm) | Geometric standard deviation | Skewness | Kurtosis | Arithmetic mean ϕ (mm) | Geometric mean ϕ (mm) | Geometric standard deviation |
| 1 | 2,557 | 9,296 | 0,138 | 0,089 | 3,302 | 2,557 | 9,296 | 0,138 | 0,089 | 3,302 |
| 2 | 2,339 | 8,536 | 0,280 | 0,163 | 4,313 | 2,339 | 8,536 | 0,280 | 0,163 | 4,313 |
| 3 | 0,377 | 2,096 | 0,071 | 0,022 | 6,328 | 0,173 | 2,403 | 0,145 | 0,024 | 7,103 |
| 4 | 1,086 | 3,478 | 0,111 | 0,049 | 4,942 | 0,947 | 3,533 | 0,148 | 0,051 | 5,186 |
| 5 | 0,628 | 2,162 | 0,165 | 0,038 | 8,584 | 0,432 | 2,240 | 0,937 | 0,098 | 14,545 |
| 6 | 0,498 | 2,146 | 0,431 | 0,072 | 10,783 | 1,136 | 3,097 | 2,113 | 0,479 | 14,099 |
| 7 | 0,065 | 1,566 | 0,277 | 0,028 | 13,638 | 0,388 | 1,668 | 1,292 | 0,109 | 23,040 |
| 8 | -0,092 | 1,538 | 0,210 | 0,019 | 13,133 | 0,026 | 1,551 | 0,804 | 0,044 | 21,304 |
| 9 | 0,229 | 1,899 | 0,261 | 0,042 | 10,490 | 0,233 | 1,902 | 0,773 | 0,079 | 14,669 |
| 10 | 2,427 | 10,866 | 0,603 | 0,365 | 3,967 | 2,113 | 9,836 | 0,792 | 0,417 | 4,254 |
| 11 | 2,207 | 9,284 | 0,581 | 0,332 | 4,164 | 1,967 | 8,617 | 0,736 | 0,372 | 4,422 |
| 12 | 2,582 | 12,093 | 0,777 | 0,507 | 3,480 | 2,193 | 10,665 | 1,048 | 0,604 | 3,757 |
| 13 | 0,651 | 1,657 | 0,553 | 0,083 | 19,595 | 0,710 | 1,800 | 0,784 | 0,107 | 20,757 |
| 14 | 0,280 | 2,169 | 0,106 | 0,024 | 6,619 | 0,126 | 2,357 | 0,191 | 0,027 | 7,493 |
| 15 | 0,245 | 2,053 | 0,095 | 0,021 | 6,761 | 0,120 | 2,237 | 0,159 | 0,022 | 7,467 |
| 16 | 0,302 | 2,022 | 0,086 | 0,024 | 6,991 | 0,287 | 2,047 | 0,092 | 0,024 | 7,050 |
| 17 | 0,461 | 2,308 | 0,225 | 0,043 | 8,143 | 0,306 | 2,294 | 0,628 | 0,070 | 11,306 |
| 18 | 0,655 | 2,499 | 0,298 | 0,070 | 8,549 | 0,553 | 2,476 | 0,827 | 0,125 | 11,458 |
| 19 | 2,261 | 7,900 | 0,307 | 0,173 | 4,774 | 2,261 | 7,900 | 0,307 | 0,173 | 4,774 |
| 20 | 1,875 | 10,030 | 0,483 | 0,292 | 3,260 | 1,500 | 8,777 | 0,611 | 0,321 | 3,524 |
| 21 | 0,427 | 1,742 | 0,188 | 0,032 | 10,739 | 0,367 | 1,840 | 0,296 | 0,036 | 11,882 |
| 22 | 0,118 | 1,429 | 0,168 | 0,021 | 12,537 | 0,084 | 1,530 | 0,265 | 0,024 | 13,849 |
| 23 | 0,167 | 1,445 | 0,169 | 0,023 | 12,626 | 0,134 | 1,535 | 0,250 | 0,026 | 13,686 |
| 24 | 0,677 | 2,100 | 0,290 | 0,055 | 11,325 | 0,625 | 2,178 | 0,463 | 0,067 | 12,631 |
| 25 | 0,203 | 1,418 | 0,271 | 0,028 | 15,209 | 0,204 | 1,503 | 0,445 | 0,036 | 17,384 |

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Appendix 9. Continued.

| | Data on basis <2 mm diameter | | | | | Data on basis <6 mm diameter | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Sample No. | Skewness | Kurtosis | Arithmetic mean ϕ (mm) | Geometric mean ϕ (mm) | Geometric standard deviation | Skewness | Kurtosis | Arithmetic mean ϕ (mm) | Geometric mean ϕ (mm) | Geometric standard deviation |
| 26 | 0,410 | 1,566 | 0,366 | 0,048 | 16,257 | 0,847 | 2,230 | 1,614 | 0,220 | 21,811 |
| 27 | 0,381 | 1,561 | 0,292 | 0,039 | 14,526 | 0,506 | 1,823 | 1,020 | 0,096 | 20,612 |
| 28 | 0,603 | 1,924 | 0,310 | 0,054 | 12,606 | 0,618 | 2,131 | 0,885 | 0,105 | 16,520 |
| 29 | 0,117 | 1,342 | 0,340 | 0,032 | 18,317 | 0,638 | 1,780 | 1,571 | 0,162 | 26,811 |
| 30 | 0,160 | 1,359 | 0,288 | 0,032 | 17,052 | 0,253 | 1,497 | 0,732 | 0,056 | 21,989 |
| 31 | 0,735 | 2,119 | 0,410 | 0,076 | 13,069 | 0,959 | 2,681 | 1,442 | 0,238 | 16,689 |
| 32 | 0,246 | 1,423 | 0,342 | 0,039 | 17,168 | 0,380 | 1,593 | 0,879 | 0,077 | 22,127 |
| 33 | 0,066 | 1,404 | 0,326 | 0,030 | 17,036 | 0,229 | 1,492 | 0,877 | 0,063 | 23,138 |
| 34 | 1,142 | 3,507 | 0,269 | 0,090 | 7,091 | 1,075 | 3,494 | 0,326 | 0,095 | 7,379 |
| 35 | 1,159 | 3,512 | 0,270 | 0,090 | 7,102 | 1,067 | 3,492 | 0,351 | 0,098 | 7,515 |
| 36 | 0,859 | 2,322 | 0,193 | 0,053 | 9,403 | 0,838 | 2,341 | 0,214 | 0,054 | 9,563 |
| 37 | 0,422 | 1,520 | 0,167 | 0,031 | 12,092 | 0,417 | 1,531 | 0,175 | 0,031 | 12,190 |
| 38 | 0,462 | 1,577 | 0,158 | 0,031 | 11,501 | 0,445 | 1,610 | 0,182 | 0,032 | 11,760 |
| 39 | 0,470 | 1,575 | 0,174 | 0,031 | 11,747 | 0,452 | 1,614 | 0,206 | 0,033 | 12,100 |
| 40 | 0,122 | 1,386 | 0,171 | 0,021 | 12,932 | 1,302 | 3,176 | 2,543 | 0,538 | 20,220 |
| 41 | 0,685 | 2,371 | 0,133 | 0,039 | 6,835 | 0,685 | 2,371 | 0,133 | 0,039 | 6,835 |
| 42 | 1,564 | 5,183 | 0,450 | 0,184 | 6,170 | 1,396 | 4,974 | 0,662 | 0,221 | 6,750 |
| 43 | 1,387 | 4,636 | 0,442 | 0,170 | 6,194 | 1,259 | 4,493 | 0,602 | 0,196 | 6,679 |
| 44 | 0,467 | 1,537 | 0,329 | 0,050 | 16,168 | 0,470 | 1,576 | 0,393 | 0,054 | 16,733 |
| 45 | 2,303 | 10,817 | 0,418 | 0,247 | 3,639 | 2,112 | 10,254 | 0,474 | 0,258 | 3,769 |
| 46 | 2,539 | 10,180 | 0,544 | 0,298 | 4,656 | 2,371 | 9,750 | 0,647 | 0,322 | 4,848 |
| 47 | 1,524 | 4,185 | 0,387 | 0,145 | 8,030 | 1,453 | 4,181 | 0,499 | 0,161 | 8,415 |
| 48 | 0,335 | 1,493 | 0,204 | 0,035 | 12,911 | 0,322 | 1,532 | 0,244 | 0,037 | 13,337 |
| 49 | 0,828 | 2,245 | 0,102 | 0,030 | 6,671 | 0,795 | 2,282 | 0,117 | 0,031 | 6,808 |
| 50 | 0,202 | 1,442 | 0,061 | 0,016 | 8,615 | 0,202 | 1,442 | 0,061 | 0,016 | 8,615 |

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Appendix 9. Continued.

| | Data on basis <2 mm diameter | | | | | Data on basis <6 mm diameter | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Sample No. | Skewness | Kurtosis | Arithmetic mean ϕ (mm) | Geometric mean ϕ (mm) | Geometric standard deviation | Skewness | Kurtosis | Arithmetic mean ϕ (mm) | Geometric mean ϕ (mm) | Geometric standard deviation |
| 51 | 1,239 | 3,300 | 0,102 | 0,040 | 5,243 | 1,239 | 3,300 | 0,102 | 0,040 | 5,243 |
| 52 | 0,431 | 1,580 | 0,077 | 0,021 | 8,340 | 0,431 | 1,580 | 0,077 | 0,021 | 8,340 |
| 53 | 0,973 | 2,858 | 0,324 | 0,091 | 8,878 | 0,889 | 2,885 | 0,491 | 0,108 | 9,720 |
| 54 | 1,279 | 3,324 | 0,376 | 0,102 | 9,630 | 1,239 | 3,348 | 0,459 | 0,111 | 10,030 |
| 55 | 1,648 | 5,308 | 0,437 | 0,170 | 6,513 | 1,501 | 5,143 | 0,614 | 0,199 | 7,037 |
| 56 | 1,420 | 4,031 | 0,064 | 0,029 | 4,006 | 1,420 | 4,031 | 0,064 | 0,029 | 4,006 |
| 57 | 1,637 | 4,919 | 0,072 | 0,039 | 3,996 | 1,637 | 4,919 | 0,072 | 0,039 | 3,996 |
| 58 | 1,527 | 4,238 | 0,087 | 0,044 | 4,757 | 1,527 | 4,238 | 0,087 | 0,044 | 4,757 |
| 59 | 0,741 | 2,501 | 0,167 | 0,036 | 7,111 | 0,430 | 2,554 | 0,573 | 0,059 | 10,536 |
| 60 | 1,609 | 4,662 | 0,143 | 0,058 | 5,188 | 1,609 | 4,662 | 0,143 | 0,058 | 5,188 |
| 61 | 1,489 | 4,124 | 0,135 | 0,051 | 5,386 | 1,357 | 4,116 | 0,179 | 0,054 | 5,681 |
| 62 | 1,849 | 5,840 | 0,522 | 0,219 | 6,308 | 1,827 | 5,820 | 0,549 | 0,224 | 6,374 |
| 63 | 1,772 | 5,875 | 0,554 | 0,236 | 6,095 | 1,651 | 5,723 | 0,732 | 0,273 | 6,479 |
| 64 | 1,902 | 6,056 | 0,227 | 0,115 | 4,896 | 1,885 | 6,041 | 0,233 | 0,115 | 4,920 |
| 65 | 0,949 | 2,549 | 0,113 | 0,044 | 7,046 | 0,769 | 2,678 | 0,203 | 0,048 | 7,732 |
| 66 | 1,581 | 5,268 | 0,360 | 0,153 | 5,429 | 1,352 | 4,989 | 0,541 | 0,180 | 6,020 |
| 67 | 0,396 | 1,560 | 0,211 | 0,034 | 12,839 | 0,381 | 1,597 | 0,250 | 0,036 | 13,262 |
| 68 | 2,524 | 8,902 | 0,670 | 0,365 | 5,509 | 2,491 | 8,856 | 0,710 | 0,376 | 5,563 |
| 69 | 2,769 | 10,621 | 0,746 | 0,430 | 5,054 | 2,698 | 10,489 | 0,827 | 0,455 | 5,142 |
| 70 | 1,095 | 3,523 | 0,340 | 0,103 | 7,073 | 1,046 | 3,506 | 9,394 | 0,109 | 7,326 |
| 71 | 0,529 | 2,118 | 0,169 | 0,034 | 8,706 | 0,389 | 2,235 | 0,332 | 0,041 | 10,244 |